HEAT TREATMENT OF TOOL STEEL

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HEAT TREATMENT OF TOOL STEEL

AN ILLUSTRATED DESCRIPTION OF THE PHYSICAL CHANGES AND PROPERTIES INDUCED IN TOOL STEEL BY HEATING AND COOLING OPERATIONS

BY

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WITH ILLUSTRATIONS

LONGMANS, GREEN, AND CO.

39 PATERNOSTER ROW, LONDON

NEW YORK, BOMBAY, AND CALCUTTA

1911

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BY THE AUTHOR

PREFACE

THE following pages are intended to be helpful to the trained artizan and foreman, whose business it is to produce steel objects and tools for various purposes. Also to the merchant, manufacturer's representative, and other official, who frequently meet complaints which they would like to fathom, and are often called upon to assume a knowledge of the properties of steel somewhat out of proportion to the opportunities afforded by the daily routine of their business.

In the steel trade, perhaps more than in any other trade, the consumer looks to the manufacturer to furnish instructions about all materials and processes relating to the properties of steel. This state of affairs arose quite naturally at a time when the means at our disposal for investigating and classifying tool steels were confined exclusively to an examination of the fractured ingot or bar. This kind of examination the steelmaker developed into an art, which he practised with wonderful proficiency and accuracy long before the science of analytical chemistry was competent to replace his "tempers" by percentages of carbon.

From the combined experience of the maker and user of steel there arose eventually a system whereby material of approximately the same kind was supplied, from whatever source it came, for the same purpose. As this system was based on appearances intelligible only to the competent steelmaker, it was inevitable that he should, in most cases,

become arbiter and judge as to defects and remedies incidental to the heat treatment of tools.

Although the small ingots into which tool steel is originally cast are still for the most part graded according to the appearance of their fractured surfaces, it has long been possible for general purposes, to replace arbitrary signs denoting "tempers" by definite figures representing chemical composition. In this form the "temper" of a steel bar, and its fitness for any particular purpose may be understood and appreciated by the user quite as intelligently as by the maker. The observant toolmaker, therefore, assisted by his personal experience, should be equally as competent as the steelmaker to face his own difficulties.

The ultimate value of a tool may depend as much on the manner in which it is worked into its finished shape, as on the material from which it is made. The skill and knowledge of the toolsmith and hardener must therefore always be taken into account. If for any reason whatever these cannot be relied upon, then softer steels which are not so readily overheated in forging, or cracked in hardening, are invariably introduced at the cost, and finally to the dissatisfaction, of the tool user.

Reference is repeatedly made in the text to the value of patient observation and careful experiment, in however modest a degree they may be exercised. The writer hopes that the subsequent pages, aided by these twin brothers, will enable the toolmaker to improve his products, and also to locate and avoid some of his troubles. He may at any rate easily convince himself that the destiny of his tools is not altogether in the hands of the steelmaker, and that not all defective and broken tools can justly be ascribed to bad steel, but are often due rather to various causes which may be detected and remedied.

The Author is greatly indebted to his colleagues for

the cheerful manner in which they have offered their leisure and special talents: Stone in making drawings, Atkinson in reading proofs and preparing the Index, Wild in making photographs, and Nelson in making an orderly arrangement of much of the text from rough pencil notes. He is also inexpressibly indebted to the firm of Thos. Firth & Sons for pleasant associations, and the exceptional facilities afforded by their works at home and abroad.

H. B.

THE RESEARCH LABORATORY,
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STRUCTURE AND CLASSIFICATION

THE tool-maker is not at all interested in the question "What is steel?" from the point of view of learned societies and congresses. He is, however, very much concerned with the differences which confer on this material the properties of a good sate, on that the qualities required by a drill, and on the other the virtues looked for in a turning tool.

It is important, also, that he should appreciate the changes brought about in the physical properties of steel by case-hardening, water quenching, tempering, annealing, and so on. He may further, once the rudiments have been understood, proceed to a consideration of the principles underlying the properties of the newer alloy steels of which one now reads so much and understands so little. He may ultimately do much to dispel our ignorance of many material things which can be more favourably observed in the shop than in the laboratory, and more sharply corrected by experience than by our too-little-suspected theories.

CRYSTALLINE STRUCTURE.

Every mechanic has seen a brass or a steel casting, a burnt furnace-bar or some other metal object snapped in two, and has observed the coarse staring kind of fracture made up of crystalline particles, having sharp edges and shining flat faces, as represented in Fig. 1.

This kind of structure on a greater or less scale is present in every metal or combination of metals, although the ideal geometrical forms to which the crystalline grains approximate may vary. Owing to rapid cooling or the pressure exerted by the hammer or rolls the crystalline grains are often very ill-defined and hardly distinguishable to the naked eye. All commercial kinds of steel belong to this

category and must be examined by means of a microscope in order to elucidate their structure.

MICRO-STRUCTURE.

To see the collection of small crystals packed into a piece of forged metal no larger perhaps than a good-sized pin's head it is necessary to apply high magnifying powers to a flat surface. This means, of course, that in a section through the minute crystals there will be seen something like Fig. 2, which represents the microstructure of pure iron.

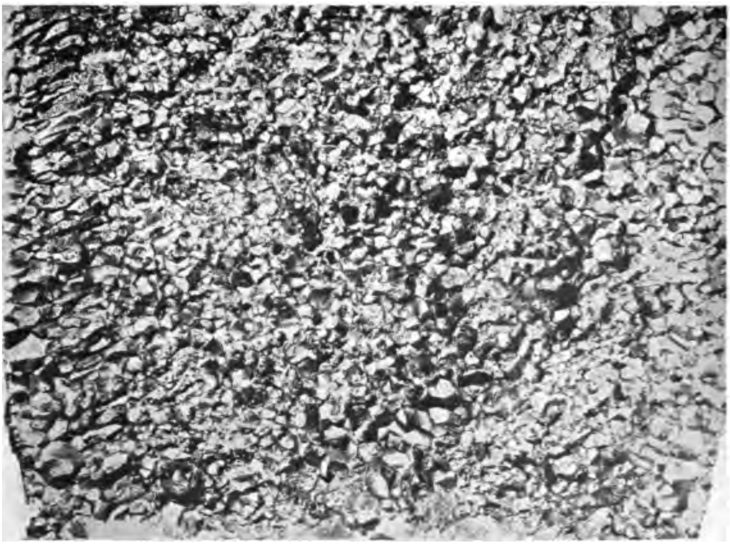


FIG. 1.—Crystalline racture of large steel casting. Linear reduction about one-third.

The resistance of such an agglomeration of unit crystals either to steady pressure or impact forces will depend—

1. On the strength of the material of which the grain consists.

2. On the cohesion between the respective grains.

In pure metals which have been well wrought the former is generally quite as easily overcome as the latter, though cohesion between the grains is usually lessened by improper heat-treatment and frequently very much so by the presence of impurities.

In some cases it happens that when one metal is alloyed

with another it does not in any way interfere with the form of the crystalline grains. A silicon-iron alloy, for example, containing, say, 3 or 4 per cent. of silicon, would appear exactly like Fig. 2, except that, after similar treatment, the grains would be larger. The addition of a small amount of chromium would also be indistinguishable in the form, though it would decrease the size, of the grains. In the study of alloys of this kind, many of which exist, the microscope is not especially helpful. On this account the presence of silicon, manganese, chromium, nickel, and some other

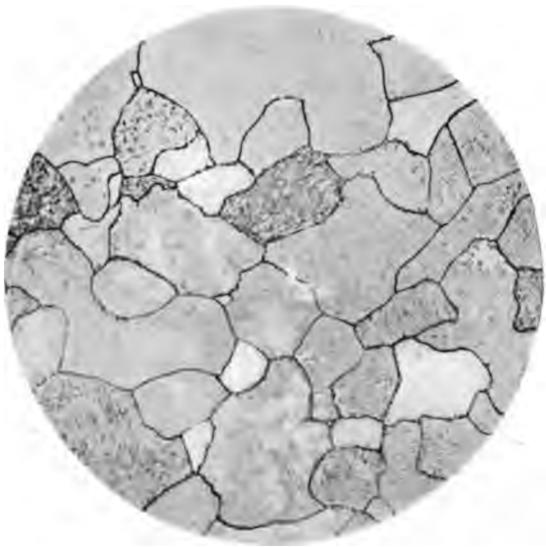


FIG. 2.—Microstructure of pure iron. Photo by Guertler.

elements commonly added to steel are not directly distinguishable. On the other hand, some elements on being alloyed with a second can easily be detected even in minute quantities, and it is thus possible to observe microscopically the structural changes taking place as the relative amounts of the two original substances are varied. In considering carbon and iron as a particular example of this class of alloys, we shall see more clearly than in any other way how wrought iron becomes transformed into steel.

IRON AND CARBON.

The effect of introducing even less than one-tenth of one per cent. of carbon into iron is easily visible in a properly

prepared specimen examined with the microscope. In addition to the regular polyhedric crystals, which are practically alike, there now appears a number of dark areas as exemplified by Fig. 3. Practically all the carbon introduced is confined to these dark areas, the remaining portion of the observed field consisting as before of pure iron, which as a micro-constituent is known as ferrite.

PEARLITE. If the dark areas were highly magnified and the steel in which they exist had been slowly cooled from a good red heat, say 800° C., then they would have the appearance of

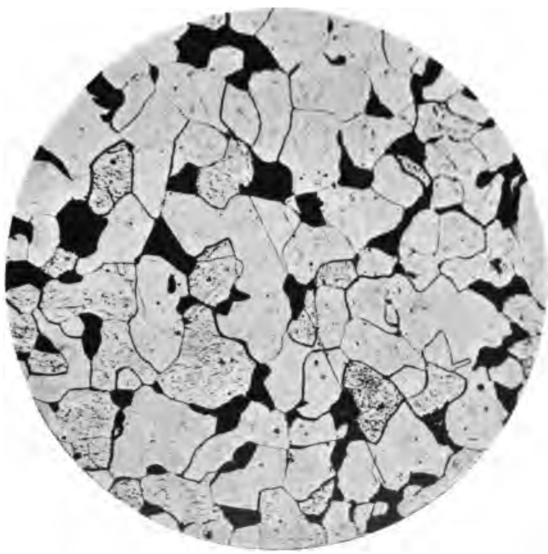


FIG. 3.—Iron containing 0·15 per cent. of carbon. Magnified 100 diameters.

black and white lines arranged alternately and roughly parallel to each other. This arrangement is common amongst metallic alloys, and is characteristic of what are called eutectics. At present the object is merely to call attention to a fact of which we have later to make some use and not to discuss the cause and condition of eutectics, which is somewhat outside the scope of our purpose. It should, however, be remarked that the striated appearance of the dark areas seen in Fig. 4 is really due to a compact arrangement of alternate plates of pure iron and carbide of iron (Fe_3C) after selective etching.

When the striation is sufficiently well-defined, as is usually the case in annealed tool steel, it breaks up light-waves just like the surface of a pearl and for the same reason. On this account the dark areas when first observed by Dr. Sorby were called the " pearly constituent," and are now spoken of briefly as " pearlite."

All mild steels then, considered microscopically, are composed of ferrite [1] and pearlite.

The relative areas occupied by these constituents in a piece of slowly cooled steel depend on the amount of carbon

FIG. 4.—Steel containing 0·45 per cent. of carbon—very slowly cooled.

present. Fig. 3 is a typical appearance of a steel containing 0·15 per cent. carbon; Fig. 4 represents a steel containing 0·45 per cent. carbon, and Fig. 5 the appearance of a steel containing about 0·75 per cent. carbon, in which case the pearlite areas are completely surrounded by envelopes of ferrite.

From this point onwards the ferrite envelope becomes

[1] For the sake of directness we are assuming that steel is simply an alloy of iron and carbon. As a matter of fact steels always contain small amounts of silicon, manganese, sulphur, and phosphorus, which do not, however, interfere much with the micrographic appearance.

thinner as the percentage of carbon introduced becomes greater, and ultimately when the carbon reaches approximately 0·90 per cent. the ferrite disappears; that is to say it becomes entirely monopolized by the carbon to form pearlite.

The point in composition at which free ferrite ceases to exist in steel is, as we shall see later, of exceptional interest to the tool-maker, and like many other industrial facts of great importance, it had been observed and appreciated long before any scientific explanation was available.

CEMENTITE.

After having utilized all the free iron (ferrite), it is clear

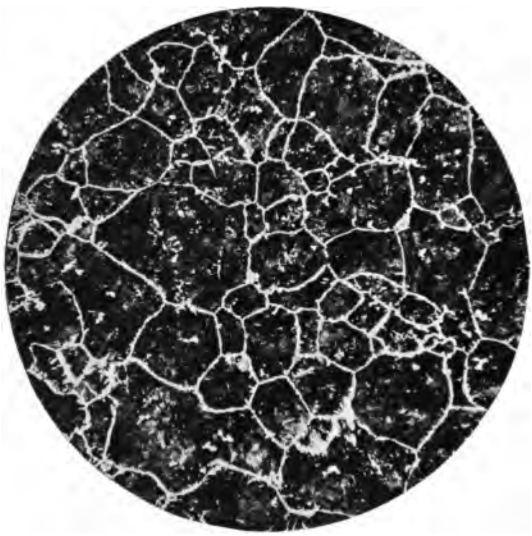


FIG. 5.—Steel containing 0·75 per cent. carbon. Magnified 100 diameters.

that if any further amount of carbon can be introduced into the steel it must adapt itself to some new form of existence. It is found on observation that further additions of carbon form a new constituent which exists either as isolated plates within or as envelopes around the crystalline grains of pearlite. This constituent, which is known as cementite, is identical in composition with those plates of iron carbide arranged in alternate layers with pure iron to form pearlite. So that no matter how much carbon is introduced into steel it forms always the same carbide—Fe_3C. As long, however, as free iron is available the carbide arranges itself

alternately, that is to say sandwich-wise with it; when, however, free iron is no longer available the carbide exists

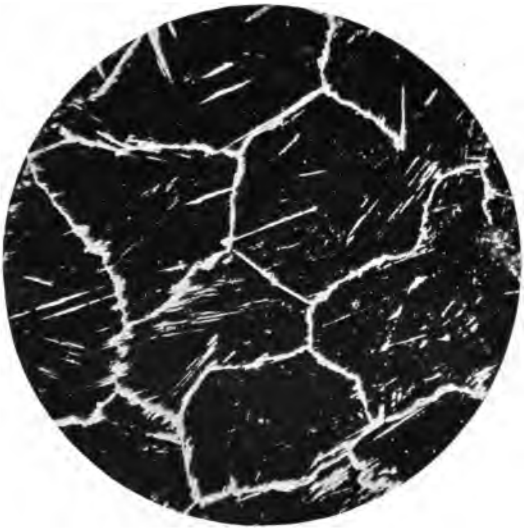


FIG. 6.—Free cementite in 1·40 per cent. carbon steel.

FIG. 7.—Free cementite needles in case-hardened steel.
Photos at 100 diameters.

alone (Figs. 6 and 7), and is naturally present in greater amounts as the percentage of carbon rises.

From the foregoing it appears that the introduction of carbon into iron to produce steel modifies its properties by forming within it a new or distinctly separate substance called carbide of iron. This carbide is exceedingly hard, harder in fact than the mass of hardened steel, and consequently brittle. It is very finely dispersed and intimately mixed with the iron so long as the amount of carbon does not exceed one per cent., but any excess beyond this exists in a comparatively coarse state.

PHYSICAL PROPERTIES.

From these considerations, and attentive observation of Figs. 2 to 7, it is obvious that the hardness of steel will increase as the pearlite grains occupy a larger portion of the material. It is equally obvious that the toughness will decrease as the ferrite grains, which are composed of soft flexible iron, become less. But the toughness may still be considerable, so long as each small plate of hard carbide is cushioned between two plates of soft iron, that is until the amount of carbon approaches one per cent.

When the carbide is free to form comparatively large plates, or to form brittle envelopes separating each grain from its neighbour, the intergranular cohesion is enormously weakened. We are able, therefore, to take advantage of the great hardness of steel containing free carbide (cementite) only for such purposes as involve no sudden or violent blows, as, for example, turning tools, razors, scythes, etc. If hammers or cold sates were made from such steels they would, as may easily be imagined, quickly break up along the brittle crystalline junctions.

For such purposes as require tools to withstand rough usage, and at the same time demand a hard cutting edge, a steel containing, for obvious reasons, little or no cementite must be chosen; whilst for many purposes, such as drop forging dies, cold sates, boiler-makers' snaps, etc., the toughness of the objects may be still further increased by using much milder steels, and sacrificing that portion of the hardness which is not imperative.

GRADING STEEL.

Having seen that the efficiency of a tool depends to a great extent on the kind of steel from which it is made, it is easy to understand why the steel-maker usually requests the purchaser to state the purpose for which the required

steel is intended, as it is in practice by no means very rare to find tools made from quite unsuitable material otherwise excellent in quality. In order to avoid such errors it is customary to indicate by label and stamp the purpose for which any particular bar of steel may be satisfactorily used. The table on p. 10 is a representative list of such purposes together with the approximate amount of carbon present in the respective steels, and the older names by which the tempers were formerly distinguished.

TEMPER.

All carbon steels are classified according to their temper and quality. Temper is used by the steel-maker (as a noun) to denote the natural degree of hardness, which can be varied by the introduction of more or less carbon.[1]

The natural hardness can of course also be varied by introducing manganese, chromium, tungsten, etc., but the word had, before the value of these admixtures was realized, acquired a definite meaning, which is still reserved for Carbon Tool Steels pure and simple, containing rarely more than 0·4 to 0·6 per cent. altogether of any elements other than iron and carbon.

QUALITY.

Quality cannot be defined in the same concrete manner. It refers generally to the absence of harmful impurities attained by selecting the purest raw materials, and the virtues conferred by manipulating them carefully in the way experience has shown to be the best. Since for many years the reliability and durability of steel has been influenced by the addition of helpful ingredients, as well as by the exclusion of harmful impurities, the sense in which the word "quality" is used tends to become less exclusive.

[1] The use of the word "temper" (as a verb) in a somewhat different sense is justified and quite well understood by the practical hardener. But the use of the word "temper" by translators, and persons more or less remotely connected with the usages of the steel trade, to denote a change brought about by quenching from a high temperature, which every craftsman calls hardening, leads to confusion and should be abandoned entirely.

Temper.	Approximate Carbon.	Used for.
Die temper	0·70–0·75 %	All kinds of dies for deep stamping, pressing, and drop forgings, mining drills to harden only. EASILY WELDABLE.
Smith's tool temper	0·80–0·85 %	Large punches, minting and rivet-dies, nailmakers' tools, hammers, hot and cold sates, snaps and boiler-makers' tools, various smiths' tools, large shear blades, double-handed chisels, caulking tools, heading dies, masons' tools, and general welding purposes.
Shear blade temper	0·90 %	Punches, large taps, screwing dies, shear blades, table cutlery, circular and long saws, heading dies. WELDABLE.
General purposes temper	0·90–0·95 %	Taps, small punches, screwing dies, saw-webs, needles, etc., and all general purposes. WELDABLE.
Axe temper	0·95–1·05 %	Axes, chisels, small taps, miners' drills, and jumpers to harden and temper, plane irons. WELDABLE WITH CARE.
Cutlery temper	1·0–1·1 %	Large milling cutters, reamers, pocket cutlery, wood tools, short saws, granite drills, paper and tobacco knives. WELDABLE WITH VERY GREAT CARE.
Tool temper	1·2–1·3 %	Turning, planing, slotting and shaping tools, twist drills, mill picks, scythes, circular cutters, engravers' tools, surgical cutlery, circular saws for cutting metals, bevel and other sections for turret lathes. NOT WELDABLE.[1]
Razor temper	1·3–1·4 %	Razors, barrel boring bits, special lathe tools for turning chilled rolls. NOT WELDABLE.

[1] This refers only to ordinary shop methods of welding; the steel can be welded to itself with a suitable flux and careful handling.

II

FRACTURES AND EXTERNAL APPEARANCES

THIS subject, considered in its logical order, should follow the study of forging and rolling operations. As, however, the tool-maker looks upon finished bars as raw material, he should be able, at the outset, to recognize those physical defects which are likely to lead to failure.

An ingot as cast is not always a perfectly continuous and homogeneous piece of material. Apart from segregation, which is rarely appreciable in small crucible steel ingots, there exists always the possibility of piping and blow-holes.

PIPE.

Pipe may be defined as the cavity formed by shrinkage as the molten metal passes gradually from the liquid to the solid state. Half a century ago or less, the only remedy was to "top" the ingot after it had become cold: this operation is still performed, but the wastage is much less than formerly, because the upper part of the ingot mould is now lined with a white-hot fireclay sleeve—called a dozzle—which keeps the top portion of the metal molten, and free to move downwards as the shrinkage takes place.

HARD CENTRE.

In order further to increase the fluidity of the steel in the dozzle, a layer of fine charcoal is sometimes spread over the surface. The burning charcoal maintains the temperature, it is true, and also preserves the upper layer of metal in the fluid state longer than would otherwise be the case, but at the same time it carbonizes it. See Fig. 8.

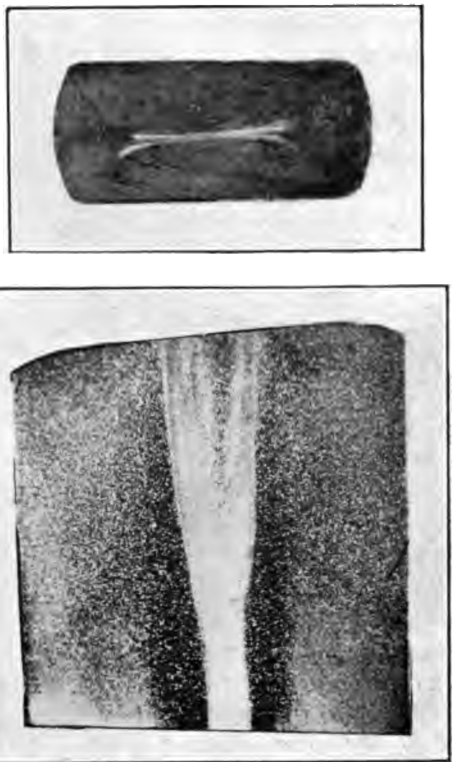
So long as the metal settles evenly in the dozzle only the upper layers, which are subsequently scrapped, become carbonized, and no possible objection to the practice can be raised. If, however, the carbonized metal, owing to a badly heated dozzle or what not, should chance to run into the

ingot itself, then the remedy in its ultimate consequences may be worse than the disease. A bar made from such an ingot would be much harder in the centre, along some portion of its length than elsewhere. The difference would be visible in the fractured surface and might become very pronounced if a section were polished and etched. A

FIG. 8.—Effect of charcoal in dozzle.

photograph of a chisel section with a hard centre is reproduced in Fig. 9 Such a bar of steel would make chisels apt to splinter at the cutting edge. Fig. 9*a* shows a longitudinal section through a cogged bar ; made into tools, this might have caused much or little trouble according to the kind of tool into which it had been made. It would, however, in nearly every case be detected and rejected in the steel-maker's warehouse.

Blow-holes also, like pipes, were formerly more numerous in tool steel ingots than they are to-day. On that account it was the practice to cog and weld all high quality tool steel before it was tilted into bars. The welding operation consisted in covering the hot bars with a fusible clay, bringing them to a yellow heat, and hammering them in order to produce sound bars free from surface defects BLOW-HOLES.



FIGS. 9 and 9*a*.

Although blow-holes and surface defects are now less numerous in ingots, they have by no means entirely disappeared; and sometimes in an altered form they survive the more modern methods of production, escape the pneumatic chipper, and even elude the wonderfully skilled eye of the warehouse examiner.

The chief surface defects, appearing ultimately on bars ROAKS.

as longer or shorter lines, which persist as a black or grey streak on being filed are known as roaks. They are frequently caused by scale and slag filling up surface inequalities and getting hemmed in by the pressure of rolling or forging, as is shown by the magnified picture of a roak in Fig. 10.

On being hardened, roaky bars frequently split right to the centre, especially if the steel hardens intensely. Chromium steel, for example, is especially subject to surface defects, and under some circumstances will invariably split

FIG. 10.—Roak in a cogged bar of mild steel. Magnified 12 diameters.

on hardening unless the rolled surface has first been machined away.

CRUSHING. The surfaces of internal defects, such as blow-holes, which have failed to weld up, always show some signs of polish caused by moving over each other. The surfaces are also flat and therefore easily distinguishable from internal defects due to crushing in an insufficiently heated state between the rolls. Defects due to crushing arise less frequently in the mill than in the tool room, and will be more fully considered in a subsequent chapter.

LAPS. Laps are caused by a fash getting bent over on to the work and rolled in. It is easy to distinguish a lap from a crack, though either may be fatal. The former runs from its extreme edge obliquely into the bar; the direction of the latter is always towards the centre. When steel is forged into complex shapes and twisted about so that the centre of a billet gets displaced towards the surface of the forging, then a crack may be disclosed on machining which is not a lap, although it runs in an oblique direction into the steel. A lap originates on the surface of heated steel, and if examined under the microscope is found to enclose a layer of scale between two layers of ferrite which were originally decarbonized surfaces.

REELING. The appearance of the surface of a bar, apart from any question of local defects, indicates more or less the temperature at which the bar left the finishing rolls. But a prejudice prevails amongst purchasers in favour of a smooth highly polished blue surface, and many rolled bars therefore are reeled or otherwise worked at very low redness and sometimes beyond it. This practice is more harmful than useful. The burnished surface pleases the eye and may lessen the tendency to rust, but it destroys a piece of evidence of real value anent the virtues of steel which are more than skin deep.

FRACTURES. The appearance of a fractured surface may be most misleading. It depends, in the first place, on the manner in which the fracture was made. The test piece of a good unannealed steel casting pulled in the usual form of tensile machine may be quite fibrous, but if a notched piece of the same steel be broken by a sharp blow it is always distinctly crystalline. It is therefore unwise to depend greatly on the evidence of fractures which have not been produced under known conditions. A piece notched with a three-cornered file or a hack-saw, or, best of all, with a V-shaped cutter and broken sharply at one blow exposes a fairly reliable fracture.

JUDGING FRACTURES. In material of the same kind, the fineness of the granular structure increases as the temperature at which the material has been finally rolled or hammered gets lower. This is an improvement down to a certain point, but may damage the

material if it is carried too far: that is to say, below visible redness. The fracture should therefore be neither too fine nor too coarse. Unless the temper of the steel is very high the fracture should be curved and irregular:—never straight or even jagged along straight lines.

The curved and torn appearance becomes more marked in softer steels. This important branch of the subject cannot be learned very thoroughly from books, but it is both easy and instructive to heat a few pieces from the same bar to varying temperatures—or prepare a single piece as described on p. 46—and, after cooling, study the fracture and other physical properties.

Amongst materials of different kinds the variations in fracture are of course greater, and only a foolish person would venture off-hand to fix finishing temperatures, grade the degree of hardness, and pass judgment. Still, however complex it may seem on paper, it is in actual practice possible to eliminate first one and then another variable, and finally develop a likely suspicion which can be confirmed or otherwise by simple tests.

NORMAL FRACTURES.

A fracture which may be considered normal for bar tool steel of a particular kind may be prepared from a piece which has been heated for half an hour to about 760° C., and allowed to cool in the air. Pieces of the same material, very much finer in fracture, have been finished at too low a temperature; pieces very much coarser in fracture at too high a temperature. The former, especially if it contains considerably over one per cent. of carbon, is apt to contain fine cracks quite invisible to the naked eye—or at best to be unduly strained. The latter is not sufficiently compact and strong, and will be found especially unsatisfactory if made into tools which have to withstand severe shock. The shanks of boiler-makers' snaps made from such steel readily break in the groove and split from the head, to mention only one example of the many failures which may arise from this cause.

In order to give a quantitative value to these remarks, a bar one and a quarter inches round was rolled from a three-inch billet which had been heated to the correct temperature at one end and to a considerably higher temperature at the

other end. Pieces broken from the respective ends of this bar had a very different appearance; one had a fine and the other a coarsely granular fracture. From these end pieces a rectangular bar 15 × 10 mm. was machined and notched. The notched pieces were clamped in a vice, and struck by a pendulum hammer provided with an arrangement for measuring the force of the blow. In this way the energy required to break the finely granular material was found to be 60 ft.-lbs., and to break the coarsely granular material only 10 ft.-lbs. The fractures thus exposed are arranged corner-wise in Fig. 10*a*.

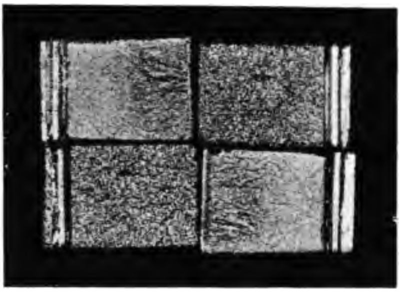


FIG. 10*a*.

DECARBONIZED SURFACES.

The skilled roller wisely insists on a "green" fire being

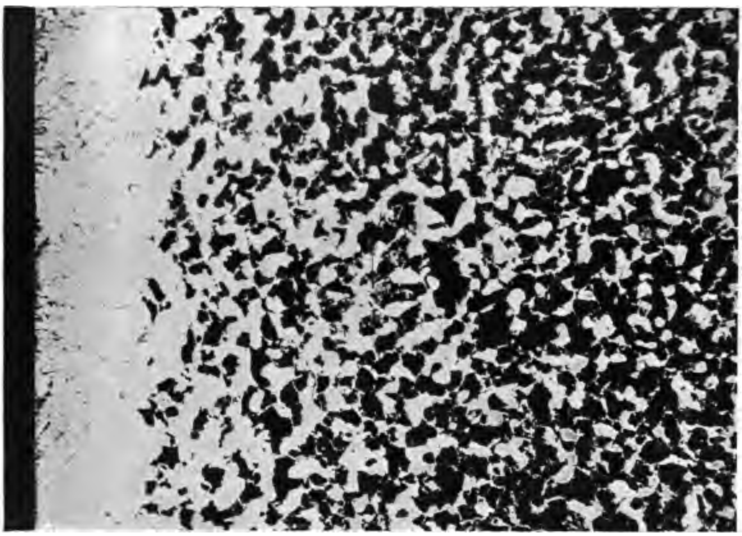


FIG. 11.—Decarbonized layer on the surface of annealed steel.

kept in the grate in order to maintain as far as practicable a reducing atmosphere in the reheating furnace. If this

precaution is neglected, or if by any chance the ingots or billets are exposed at a high temperature to an oxidizing atmosphere, the surfaces become decarbonized. The best known instance of this occurs in annealing steel castings (see Fig. 11), where the decarbonized layer may be one-eighth of an inch deep, and is rather an advantage than otherwise. On tool steel, however, a decarbonized envelope of measurable thickness may cause a great deal of trouble

FIG. 12.—Fracture of steel tool whose surface has been decarbonized.

in those uses where the bars are drawn to exact sizes; *e.g.* in the manufacture of hardened steel balls, or where the extreme surface must be made quite hard, as in the manufacture of files. If the thickness of the decarbonized layer is excessive, it may justifiably be suspected that the bar has other defects, though they may not be immediately obvious.

Either the billet has been too long or at too high a temperature in the furnace, or both, and such irregularities are nearly as objectionable in the mill as they would be subsequently in the tool room.

When quenched out in the usual manner the decarbonized surface does not harden, of course. Many complaints that steel will not harden may be traced to this cause by getting into the surface with the sharp corner of a file; the file ceases to bite as soon as metal of the normal composition is reached. If such a bar be broken the soft outer skin will bend back and form a lip, which can be felt by passing the finger gently over the broken edge, and generally be seen with an ordinary pocket lense. In extreme cases a continuous lip may be formed something like the cupped fracture of a tensile test piece (see Fig. 12).

It is sometimes claimed that steel from which the rolled surface has been machined, is on that account more likely to crack than otherwise. This may occasionally be the case, because the decarbonized outer surface resists the formation of incipient surface cracks. Generally, however, the converse is true, and there can be no question that it is safer to harden the machined bar except when surface decarbonization is excessive; in these exceptional cases perhaps the best thing to do is not to use the bar at all.

III

FORGING TOOL STEEL

AT this stage the tool-maker should recall what has been already said about coarse fractures, decarbonized surfaces, laps, etc. It applies, perhaps, with greater force to the forging of tools than to the forging of bars, as the defects arise with equal ease and remedies are more difficult to find.

CORRECT TEMPERATURE.

Two things are indispensable to good workmanship—

(1) A correct range of temperatures, from beginning to end of the forging operation, which is suited to the kind of steel being handled.

A hard steel, for example, may not be heated so freely as a softer steel without danger of burning and making the steel more or less rotten, no matter what amount of work is subsequently put on it. But a piece of overheated steel, which if allowed to cool unworked would be very fragile, regains nearly if not quite all its good qualities if forged continuously from the high heat until it is dull red. It is obvious, therefore, that the temperature at the beginning of the operation should not be greater than will enable the forging to be completed at low redness. It should also on no account be greater than that at which experience has shown the material can be safely worked without producing split edges, nor should the finished operation under any circumstances leave the material with a fracture faintly resembling that of a dog biscuit. If the forging cannot be done within the above restrictions with one heating, then it must be heated twice; nor should a temperature of 1000° C. for hard material and 1100° C. for soft material be exceeded, no matter how much work has to be done on the object.

BLUE BRITTLENESS.

Some distance below a visibly red heat, that is at about 400° C., all kinds of tool steels are very sensitive to

shock, and any mechanical operation, such as hammering, swaging, or flattening, has a great tendency to start very

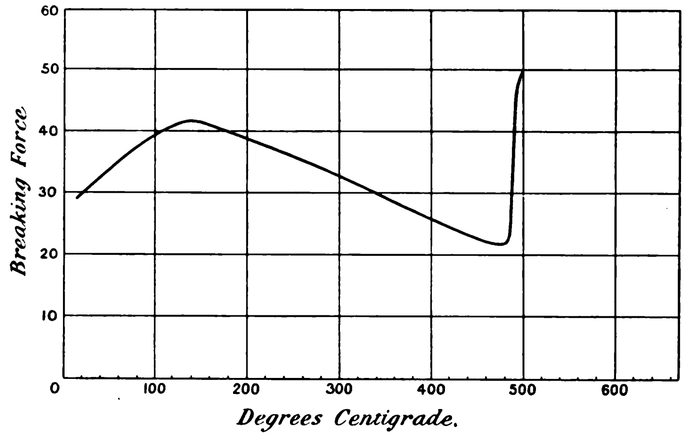


FIG. 13.—Curve representing fragility of tool steel at various temperatures.

fine cracks, which are often no broader than the hundredth part of a hair's thickness, and cannot therefore be at all distinguished by the naked eye. This property is known technically as blue shortness, because it was supposed to occur in the neighbourhood of the temperature at which the blue tempering colour is formed. A curve connecting the tendency to fracture under impact blows with the temperature which has been worked out for tool steel by Guillet & Revillon,[1] is reproduced in Fig. 13.

FIG. 13a.

The instances in which defects can be traced to blue brittleness are numerous. In forging chisels, hatchets, plane-irons, or any other wedge-shaped tool, the smith, who likes to turn out a

[1] Fifth International Testing Congress, Copenhagen, 1909.

smart-looking job, will use the flattener long after the visible red colour has disappeared from the material. The sequel is seen in the hardening shop in the form of half-moon or thumb-nail cracks (see Fig. 13*a*), until the smith learns that enough (forging) is better than too much. The characteristic thumb-nail crack can also arise from defective handling in the hardening shop, but with an example before us it is not, as we shall see, at all difficult to determine the prime cause.

It is interesting to note that blue brittleness can sometimes be turned to good account. If a bar of steel be broken cold a small flaw may exist in the fracture and pass close scrutiny; if, however, the bar be heated to about

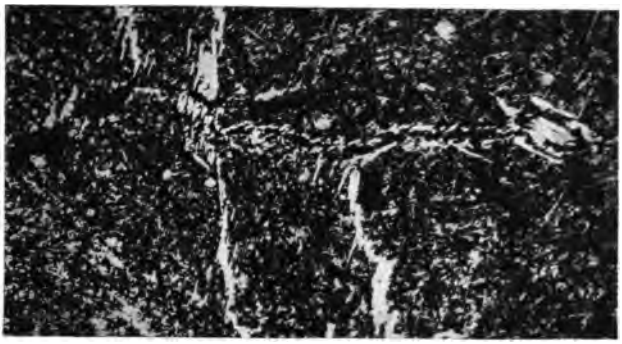


FIG. 14.—Crack following free cementite outline.

350° C. and broken, a flaw of the same magnitude would be easily detected.

CEMENTITE CRACKS.

The above considerations apply especially to very hard steel containing free cementite. The fine films of hard and brittle material provide an easy path along which the crack once started may travel. It is, therefore, necessary to prohibit the use of steel containing over one per cent. carbon, if in the subsequent rolling or forging operation any appreciable degree of cold working is unavoidable.

The micro-photograph, Fig. 14, shows clearly how the position of the free cementite cell walls coincide with the path of the crack.

FORGING ROUNDS.

A round is the most difficult of all sections of hard steel to forge without starting defects, as it is also the most risky to harden. One well-known firm of steel-makers formerly

cast all their crucible ingots in round moulds. The practice was justified by the presumption that the first blow of the hammer on the heated ingot would immediately loosen all the scale; and, further, that the round ingot presented a smaller scaling surface per unit of mass than any other shape.[1] The tool-smith should not be allured by any such considerations into working round in preference to square sections. If a round bar needs to be tapered or reduced

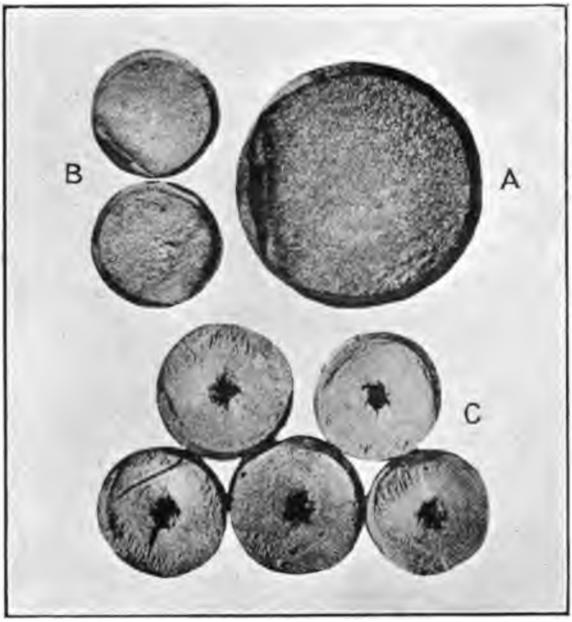


FIG. 15.—Split centres in round bars.
A represents the original bar,
B the fracture after the bar has been properly reduced in section, and
C after attempting to reduce throughout in the form of a round.

in diameter, it should first be gently flattened at the proper temperature and worked down to approximately the right size in the form of a square; then, and not before, it may be made into an octagon by knocking in the corners, and finally into the desired round. If the bar is kept round from start to finish, it is highly probable that it would

[1] Tool steel ingots are frequently cast in round moulds in German works, though for a different reason.

be split in the centre, or suffer from other defects which would lead to cracks in hardening.

The series of photographs in Fig. 15, illustrating the formation of split centres, are reproduced from the book by George W. Alling on "Points for Buyers and Users of Tool Steel."

Round bars can be rolled to smaller sections with less danger. The manner in which the stresses in the bar are moderated or magnified by its geometrical shape is considered more fully on p. 79.

UNIFORM HEATING.

The second condition indispensable to good forging is—

(2) The steel should be heated uniformly throughout and worked under a suitable hammer.

In heating large masses of steel it is necessary to proceed slowly, as the internal stresses due to unequal cooling may be increased by a sudden application of heat beyond breaking point. So far as ordinary bar steel is concerned this danger is somewhat remote, especially if the steel has been annealed; but in handling hardened tools which have to be reforged, incautious heating may cause them to clink in the centre. This serious flaw can be readily originated in the ordinary forged bars of high-speed steel by rapid heating even below redness, and, as is shown on p. 77, a hardened bar on being reheated may pull itself in two under certain circumstances. It is therefore necessary to heat any hardened piece of steel very slowly, more especially such pieces as are circular in section.

If the hammer is too small for its purpose the force of the blow does not extend to the centre of the bar, and consequently the inside and outside of the heated steel is not extended at the same rate. The same thing, or something worse, occurs in spite of a suitable hammer if the centre of the bar is colder than the outer portion. The outer portion then flows under pressure at a great rate, and the inner portion is either broken up or becomes a core over which the softer material is stretched. The disadvantage of either alternative is so obvious that no special illustration of it is necessary.

IV

ANNEALING TOOL STEEL

NO object, however simple in shape, is in an ideal state after forging; and the more complicated shapes are subject to a number of ills due to irregular extension, cold working, irregular cooling, and so on. The steel may also have a coarse crystalline structure in the thicker parts owing to want of work after being exposed to a forging heat. The object of annealing is to safeguard the tools against the accumulative effect of these ills.

MACHINING STRESSES.

It is sometimes necessary to relieve machining stresses in tools which have not been heated at all, but milled or planed direct from the annealed bar. The side of a reamer, for example, which has been milled with a blunt tool is distorted more than the remaining sides would be if cut with a sharp tool, and on hardening will warp accordingly unless previously annealed. A similar result might be expected in an object prepared in the lathe if much more material had been turned from one side of it than the other. The manner in which a blunt tool can cause distortion of a machined surface is illustrated by Fig. 16.

Such strains are of course induced more readily in mild steel than in hard steel on account of the heavier cuts taken, but the general effect is the same in either case.

ANNEALING OPERATION.

Every evil mentioned above can be remedied, at least for the most part, by careful annealing. This consists in heating the steel to the minimum temperature required for hardening, and keeping it at that temperature for a period varying from a few minutes to a couple of hours, according to the size of the object. The uniformly heated piece is then cooled uniformly and slowly until it is at least black hot.

If the prime object is to make the metal as soft as

possible for machining purposes, then the slower it is cooled down to below visible redness the better; the rate of cooling below that temperature is not as important. If forging strains only are to be removed, and the shape of the object is both simple and symmetrical, then it may be drawn from the furnace and cooled in the air, but shielded from draughts. If the removal of a structure coarsened by overheating is the sole object, then the temperature may be raised to, say, 770° C., allowed to fall to 600° C., and again raised to 770° C. before finally cooling. If the final cooling is allowed

FIG. 16.—Machining strains on surface of mild steel.

to take place at the same rate throughout the entire object, then not only has a fractured piece the finest grain it can assume in the normal unhardened state, but the material is as free as possible from tendencies which in the subsequent hardening operation might cause trouble.

The softening of steel by heating to a temperature below that at which it would harden on quenching is discussed on p. 130. Such treatment does not improve overheated structures.

The actual temperature at which steel is annealed, apart

from the rate of cooling, has considerable influence on its hardness. This is especially observable in steel containing nickel and chromium, or high amounts of manganese ; *i.e.* such steels as exhibit a tendency to air-harden. Three pieces of nickel-chrome steel which had been kept respectively at 700° C., 750° C., and 800° C. for two hours, and were then cooled at a fixed uniform rate over thirty hours, had the following mechanical properties :—

Cooled from.	Yield point.	Maximum stress.	Elongation per cent. 2 ins.	Reduction area per cent.	Brinell hardness No.
700	—	46·2	28·0	62·6	196
750	26·6	44·1	30·0	65·8	170
800	28·0	51·2	20·5	54·6	217

V

PHYSICAL CHANGES IN STEEL ON HEATING AND COOLING

FOR a better understanding of the hardening operation, it seems desirable to interpose a chapter on the physical changes which take place when a piece of steel is heated and cooled. Before the microscope and the methods of physical chemistry were applied to the study of iron and steel and other metals, the arrangement of those parts of a text-book connecting composition and properties had necessarily many points in common with the usual arrangement of a cookery-book—and the materialized instructions were sometimes equally disastrous and inexplicable. It is now, however, possible to see resemblances between the behaviour of steel and other more manageable and simpler things which enable us to think more clearly of the varied mechanical properties which may be induced in one and the same piece of steel; and also to express ourselves, or even to some extent to offer explanations, in terms of minute structural arrangements which can be observed by means of the microscope.

STRUCTURAL CHANGES

The changes which take place on heating can be most easily followed in a piece of mild steel. Take, for example, the material whose structure in the soft state is represented by Fig. 17.

STRUCTURAL CHANGES.

If a small piece of this steel were heated to any temperature below 700° C. and quenched in the coldest water, it would not harden or in any way change its structure. If, however, it were heated to 750° C. and quenched, it would afterwards be much harder and break rather than bend

over. Let us now regrind the quenched piece and observe, after preparing it for the microscope, that it still consists of black and white areas (Fig. 18).

If we tested one of the white areas with a centre punch we should find it almost as soft as wrought iron, but the dark areas struck in the same way would turn the point of the punch like a piece of hardened tool steel. The simplest way of illustrating this difference is to scratch the surface of the specimen with the point of the needle, and notice that

FIG. 17.—0·35 per cent. carbon steel in soft state.

whereas the white areas are deeply scored, the dark areas remain comparatively untouched.

MARTENSITE.

In comparing the structure of the steel, Fig. 17 before, and Fig. 18 after, the above treatment we observe: (1) that the dark areas after quenching occupy about the same proportion of the field as before, and (2), that the dark areas are no longer resolvable under any microscopic power available into alternating laminæ or any other arrangement of more than one substance. That is to say, the separate constituents of pearlite, however distinctly divided, as in Fig. 4, before heating, diffuse into one homogeneous mass when a certain temperature is reached, and may be trapped by

sudden quenching before they have time to return to their original form. This condition of diffused pearlite made permanent by sudden cooling, is known as Martensite[1] or Hardenite.

If instead of retaining our specimen for about ten minutes only at 750° C., it were kept at that temperature for a longer period; or if without altering the time the temperature were increased, then a gradual inter-diffusion of the ferrite and pearlite areas would take place as indi-

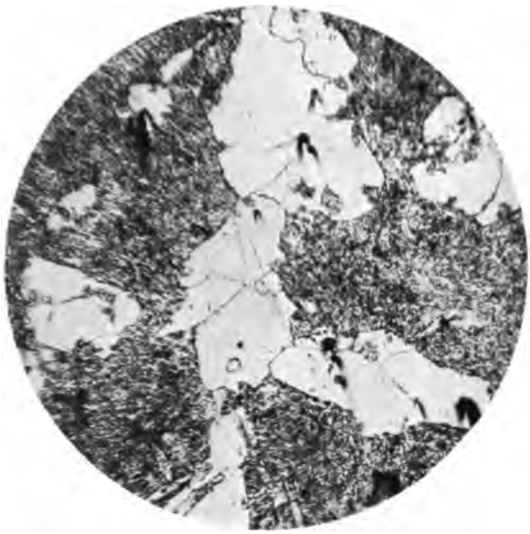


FIG. 18.—0·35 per cent. carbon steel in which pearlite areas are transformed to Martensite by water quenching after heating at 750° C. for ten minutes.

cated by Fig. 19. And finally at a higher temperature the diffusion would be complete, and no trace of the separate areas would be microscopically visible in the quenched specimen. In Fig. 20 the diffusion is nearly completed.

Although perhaps not strictly accurate, it may be said that in mild steel the property of being hardened is assumed in two stages.

(1) The transformation in the pearlite areas only, and

[1] After Martens the director of the Materialprüfungsamt in Berlin who was one of the earliest, following Sorby, to apply the microscope to the study of steel.

(2) The inter-diffusion of the transformed pearlite and the apparently unchanged ferrite areas.

HARDENING MILD STEEL.

From the above statements it may seem that the change which permits a piece of mild steel to be hardened in the pearlite areas only takes place at a lower temperature than is necessary to effect complete inter-diffusion of these with the ferrite areas. If, however, the pearlite areas cover the entire fields, as is the case when the carbon exceeds 0·9 per cent., then there is no purpose either in prolonging the time or increasing the temperature beyond the point necessary to

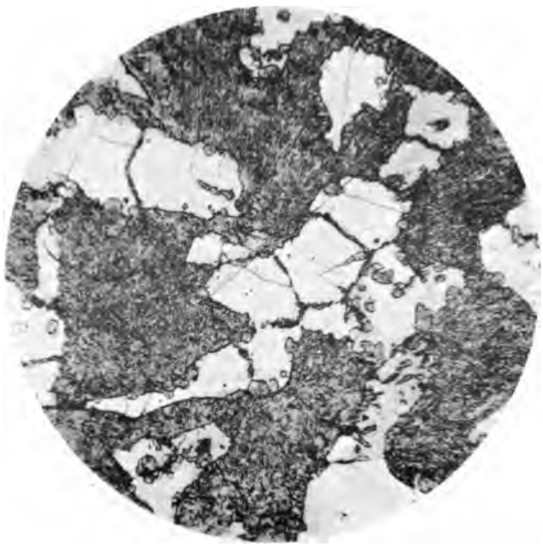


FIG. 19.—0·35 per cent. carbon steel, showing how Martensite begins to diffuse.

effect the first change. On these grounds the practice of hardening the higher carbon steels from a lower temperature is justified and explained. It is, however, quite erroneous to suppose that a piece of steel containing, say, 0·6 per cent. of carbon, could not be hardened at all at the minimum temperature required by a steel containing, say, 1·0 per cent. carbon. The same change would take place in both steels at approximately the same temperature, the only difference being that in the former a higher temperature would be necessary to obliterate the ferrite, visible in Fig. 5, for

example, whereas in the latter case this consideration does not arise because no free ferrite, either as cell walls or otherwise, exists in the steel.

SLOW COOLING.

The quenching of a piece of mild steel from a temperature well above the minimum at which it will harden, preserves the material in a state differing entirely, in a structural sense, from the normal or forged state, and probably also from the actual structure of the red-hot steel. But on allowing the specimen to cool slowly, we get back ultimately to the original starting-point through a series of

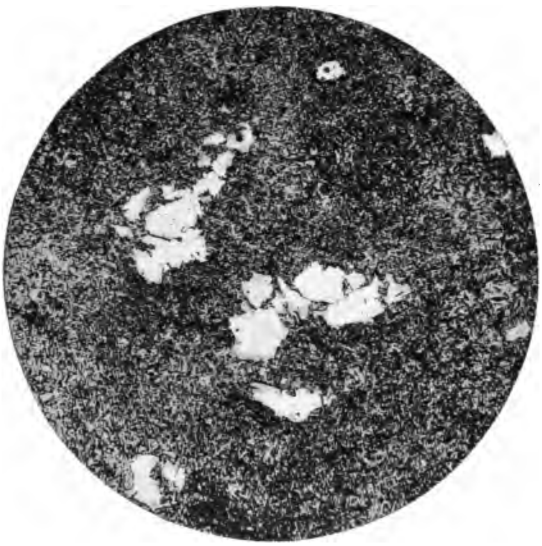


FIG. 20.—0·35 per cent. carbon steel in which the diffusion is nearly finished

changes something like the reverse of those which took place on heating. That is to say, the ferrite areas which were the last traces of the original pattern to disappear on heating, are the first to reappear on cooling. Very gradually increasing in size, they finally occupy the same relative amount of space as before ; then the black areas break up again into intimately associated plates or particles which form pearlite, and no quenching, however vigorous, once this point is passed, can cause the steel to harden appreciably. The changes may be represented broadly though not entirely by Figs. 17 to 20 taken in the reverse order.

It is not necessary to bestow more than a passing glance on the thermal behaviour of very high carbon steels containing cementite. This constituent remains in well-hardened industrial tools pretty much as it existed in the forged material from which they were made. It does not change its location or assume any very definite part in the physical changes which take place, unless the tool happens to be heated much above its minimum hardening temperature. It then diffuses into the surrounding material, and oftener than not the tool cracks on hardening. Such cracks have a great tendency to extend along the junction lines between the grains. CEMENTITE.

The use of steels containing free cementite is, as we have seen on p. 8, only permissible for tools which can be operated without shock. Its use, however, is highly advantageous under these restricted circumstances, because cementite is harder than any other constituent either natural or induced, and therefore serves a useful purpose where actual mechanical wear, as at the point of a turning tool or the hole of a draw-plate, has to be avoided.

THERMAL CHANGES

That snow or ice becomes liquid if salt is thrown on it is a fact known to everybody. If, however, a mixture of snow and salt containing 23·5 per cent. of the latter were prepared at a temperature −30° C., it would remain as dry and solid as a similar mixture of sand and sugar. But if the temperature rose only slightly above −22° C., the salt and snow would begin to interpenetrate and become first moist and then quite liquid. Above −22° C. the mixture would remain liquid; below −22° C. it would again become quite solid and consist of separate particles of ice and salt existing side by side; at −22° C. it could be either liquid or solid, but to convert it from one state to the other it would be necessary to add or subtract heat. SNOW AND SALT.

Consider also the similar behaviour of a mixture of lead and antimony. In the pure state lead melts at 327° C., and antimony at 632° C. If we prepare a mixture of very fine filings containing 13 parts of antimony and 87 parts of LEAD AND ANTIMONY.

lead, and press these together into a compact piece and again reduce it to fine filings, we shall obtain an intimate mixture of lead and antimony particles. If these be again pressed together and heated, we shall find that they melt into a perfectly homogeneous liquid at 250° C., which is considerably below the melting point of either lead or antimony. In the liquid state neither of the metals would be separately distinguishable; but in the solid state the mass will consist, however often it may have been melted, of particles or plates of lead alternating with particles or plates of antimony. The temperature of 247° C., at which the mixture begins to solidify on cooling, remains unchanged until the mass is quite solid; the temperature cannot sink before this point is reached, no matter how cold the surrounding atmosphere may be, and conversely on heating. This means that if a thermometer were placed at, say, 300° C. in the lead-antimony mixture which was being allowed to cool, we should observe a gradual and continuous fall in temperature until 247° C. was reached. Then the cooling operation would be arrested, and the thermometer kept stationary by the heat liberated during the change from the liquid to the solid state, whence it would again fall gradually to normal temperatures. This entire cooling process might be graphically represented by Fig. 21.

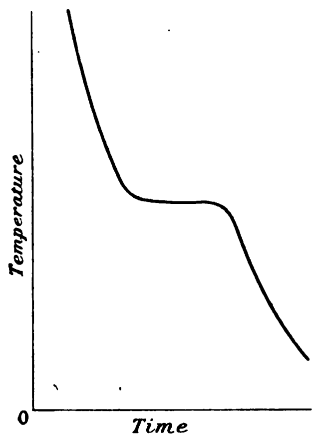


FIG. 21.—Cooling curve of eutectic mixture.

The thermal behaviour of a piece of tool steel, and many other metallic alloys, is precisely similar to the salt-snow and antimony-lead systems, which are introduced here only because any reader sufficiently interested to make personal observations will find them much easier to handle than molten and solid steel. The structural arrangement is very similar (compare Figs. 22 and 23), and the variations when

a certain temperature, characteristic of each case is reached,

FIG. 22.—Lead-antimony eutectic.

FIG. 23.—Iron-ironcarbide eutectic.

is between alternating plates of two constituents on the one hand, and solid (diffusions) or liquid solutions on the other,

heat being liberated or absorbed according to the direction of the change.

TOOL STEEL.

Owing to the liberation or absorption of heat in changing from one state to the other, we are able, by means of an arrangement for accurately measuring temperatures, to conduct a sort of thermal analysis. So far as tool steel is concerned, we need study only one typical example, *i.e.* a 0·9 per cent. carbon steel. On heating such a steel, say at the rate of one degree per second, we may represent the rise in temperature by a straight line sloping upwards. Up to a certain point the straight line correctly represents the rise in temperature, both of the steel and the furnace containing it. But at about 740° C. there occurs a period of many seconds, during which, although the furnace is getting hotter, the temperature of the piece of steel itself does not rise at all. During this period, the adjacent constituents of the pearlite are diffusing into each other, *i.e.* dissolving each other, and absorbing a certain amount of heat in the process, just as salt causes an absorption of heat and makes a freezing mixture when it dissolves in snow. As soon as this absorption of heat can no longer counterbalance the heating effect of the furnace, the temperature of the steel rises again. The entire procedure may be represented by a line, ACM, with a kink at C (see Fig. 24).

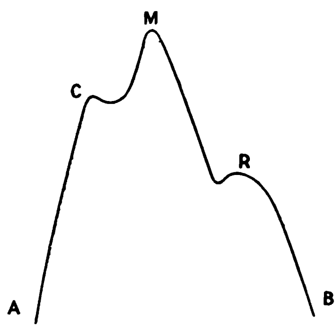


FIG. 24.—Thermal curve of 0·9 per cent. carbon steel.

It is an easy matter, by means of a delicate pyrometer suitably arranged, to follow the heating of a piece of steel in the above manner and fix the actual temperature at which the point or period C occurs. Its occurrence coincides of course with the structural changes which we connected in the last section with the property of hardening, *i.e.* only when a piece of steel has been heated beyond the temperature C can it be hardened by quenching.

But the existence of the critical point C and the actual

absorption of heat accompanying it, can be easily demonstrated in the following manner. In a smith's fire which has burned hollow, or any other uniform source of heat, place a wedge-shaped piece of steel, a chisel, for example, and notice that after becoming red-hot the extreme edge suddenly becomes colder or darker. This darker band gradually travels from the point up the thicker part of the wedge and indicates the position on the chisel in which the critical thermal change is taking place. The temperature is actually less on the darkened band than it is either above or below it, and yet if the chisel be quenched it will be hardened only up to the dark band, and not beyond it. This observation can be applied to the hardening of chisels, sates, mill-picks, axes, and numerous other tools utilized by the smith, the bridge-builder, the miller or the wood-cutter, in regions where most forms of pyrometers would be useless, although a good tool is none the less desirable. Workmen who have not the remotest idea what it means, have used this phenomenon as a "tell-tale" or indicator, to show when a desired state or degree of temperature has been attained.

To return to Fig. 24. If instead of quenching the piece of steel we allow it to cool, also at the rate of one degree per second, we observe at a temperature of 690° C., or thereabouts, a period of many seconds during which the steel does not cool at all. It may, indeed, get hotter, although all the time the furnace is cooling down. The cooling process reverses the changes which take place on heating, and may be represented by the line MRB. Both the break at R and at C are of great importance to the steel hardener, and their meaning is simply this:

From any temperature above C a piece of steel will harden if quenched, but at no lower temperature. If, however, the steel has already been heated beyond C, it can be hardened by quenching from any temperature not below R.

The points C (calescence) and R (recalescence) are known as critical temperatures or change points. Their positions do not alter much in ordinary kinds of tool steel, although the carbon may vary between 0·7 and 1·5 per

cent., but they are greatly affected by adding tungsten, chromium, or nickel to the steel.

As means for making thermal curves and observing the influence exerted on the position of the critical points by variations in composition, rate of heating and cooling, initial cooling temperature, and so on, is a desirable addition to the equipment of every first-rate hardening plant, the author has ventured to illustrate and describe on p. 140 an arrangement suitable for works purposes.

CRITICAL DENSITY CHANGES

The variable expansion on hardening of different sizes and shapes is an endless source of trouble to the maker of gauges and fine tools. How delighted he would be with a steel which on hardening neither expanded nor contracted, or even with a steel whose changed dimensions could be calculated beforehand. Such an ideal steel, however, has not yet been produced, for the simple reason that it is scarcely compatible with the nature of the hardening property of steel. Some steels, of course, come nearer the ideal than others.

VOLUME CHANGES. The volume of a piece of steel always increases on hardening, although in the case of a bar its length may shorten, and in a sheet both length and breadth generally decrease. It may, indeed, as a rule, be assumed that the main increase in size of a piece of quenched steel lies at right angles to the plane of the cooling surfaces, in other directions it often decreases. The reason for the net increase in size is that the new constituent formed above the calescence point, as made permanent by sudden cooling, has a less specific gravity than the constituents out of which it was formed. On this account the quicker the cooling, or the higher the quenching temperature (within reasonable limits), the greater is the increase in volume, though this statement is possibly not without exception.

A series of steel rods of varying thickness were hardened under the same conditions, and subsequently tempered by Fromme. He then determined their relative volumes,

taking the volume of the unhardened steel as unity, with the following results:—

Condition of rod.	Vol. of rod, 7 mm. rd.	Vol. of rod, 4·2 mm. rd.	Vol. of rod, 2·65 mm. rd.	Vol. of rod, 2·55 mm. rd.
Unhardened	1·00000	1·00000	1·00000	1·00000
Dead hard	1·00772	1·01000	1·01285	1 01210
Tempered, yellow . .	1·00347	1·00495	1·00660	1·00620
„ blue . . .	1·00217	1·00425	1·00370	1·00205
„ grey . . .	0·99957	1·00060	1·00055	0·99930

These results show not only that the thinner sections increase more in volume, but also that tempering reverses

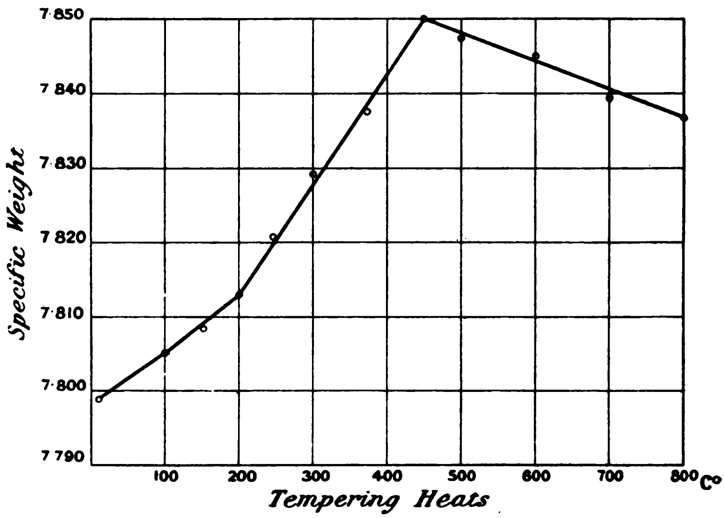


FIG. 25.—Variation in specific gravity due to tempering water-hardened tool steel.

this change. The variation in specific gravity due to tempering has been more recently investigated by Maurer, whose results are expressed diagrammatically in Fig. 25.

CRITICAL EXPANSION.

In addition to these variations in density, of which steel-hardeners are perfectly well aware, there is another critical change that takes place on cooling (and in the reverse order on heating) of which less notice has been taken, though its effects are often very serious. On cooling a bar of one per cent. carbon steel from, say, 1000° C., it shortens in length gradually and uniformly until a temperature of about

700° C. is reached. The contraction then stops and an actual and very marked expansion sets in, and at the same moment the thermal curve shows a halt in the fall of temperature. The thermal and critical expansion curves of a one per cent. carbon steel which were taken simultaneously, and explain themselves, are produced in Fig. 26.

The special importance of the critical expansion during the cooling of steel comes out in a very disagreeable manner on quenching large objects of circular section. Generally speaking, the risk of hardening a piece of round steel which requires to be glass-hard on the surface increases with its diameter. Small steel rolls, large taps, broaches and

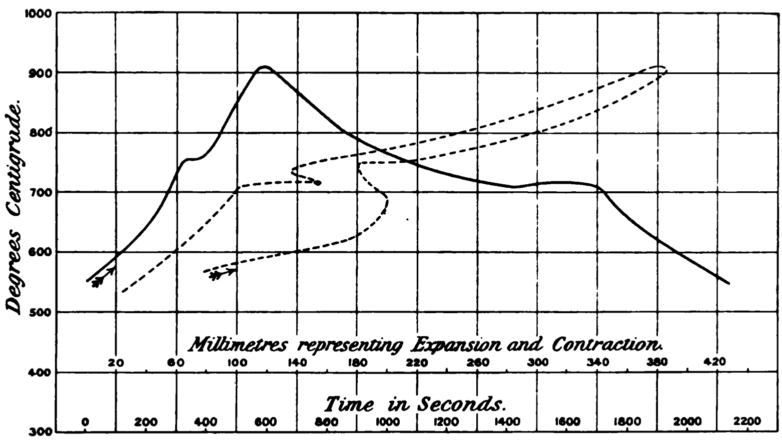


FIG. 26.

reamers will readily split along their entire length, unless carefully handled. It is frequently assumed that such tools split because "the outer parts shrink on the inner in the cooling; this evokes a reaction pressure of the inside on the outside which is greater in proportion as the temperature is greater on the outside as compared with the inside, *i.e.* the thicker the steel is.[1]

The above explanation is very difficult to follow, and may preferably be replaced by the more obvious suggestion contained in Fig. 26, viz. if the outside of a round steel object becomes quite hard before the inner portion has been

[1] Reiser, "The Hardening and Tempering of Steel," p. 23.

cooled below the temperature at which the critical expansion takes place, then, when it does take place, the hardened exterior, if it cannot yield, must break.[1] The breaking of a hardened steel ring by expansive forces from within (by a drift) takes place readily. The special danger of round bars is discussed on p. 77, and the proper handling of large-toothed cylindrical tools on p. 69. The practice of boring out the centre of steel rolls before hardening in order to prevent cracks facilitates the cooling of the inner portions below the critical temperature before the outer surfaces become quite cold and hard.

[1] On p. 9 of his highly commendable book, Edition dated 1863, Ede states that the "expansion of the middle is more than the outside can bear, and thus articles crack," but he was not able at that time to explain why the middle portions expanded.

VI

THE HARDENING OF STEEL

THE hardening operation in tool making is of the greatest importance. It shows up defects in material which were not before noticeable, and it exaggerates the faults of every previous operation. The science of it can be expressed in a few short paragraphs; the art may well become the study of a lifetime.

COMMON-PLACE REMARKS.

A piece of steel is in the best condition for hardening after it has been properly annealed. The heating of large pieces and complicated shapes should be gradual, and care taken that corners, cutting edges, and other thin parts are neither overheated nor decarbonized. These statements are very commonplace, but do not unfortunately describe the common practice. The best kind of furnace is one in which a large-enough area of it can be maintained at any desired uniform temperature. Whether this be a reverbatory hearth, or a bath of molten lead or salts, or a muffle furnace must depend on local circumstances. We have already seen that a piece of steel quenched from above the hardening temperature remains permanently expanded. But as the hardness and consequent permanent expansion on the surface and in the interior are not equal, so each piece of hardened steel of a considerable size is in the act of being pulled apart and may resist that tendency very easily or otherwise. If, however, to the unavoidable tension there is added—due to overheating—a coarse structure, which is physically weak, we have the most favourable opportunity for cracking or breaking either during or shortly after quenching. It is evident, then, that all tools should be hardened at the lowest possible temperature consistent with the desired properties, and the whole science and art of hardening resolves itself into attaining this temperature

in a regular and uniform manner, and in quenching the heated tool with due regard to its size, shape, etc., and the work it is required to do.

UNIFORM HEATING.

Uniform heating is much more important than a variation of a few degrees in the actual temperature, and can only be attained in a suitable furnace. The salt bath most nearly approaches the ideal kind of furnace, and is to be recommended for expensive tools wherever possible. The lead pot is also excellent; it heats objects more quickly than a salt bath, and for some purposes is to be preferred. A flat hearth gas-fired furnace is less reliable than either of the above, though it may sometimes be more convenient. If closed muffle furnaces are used, the temperature is more uniform with cast-iron or steel muffles than with fireclay ones. The worst form of furnace is the ordinary smith's hearth, though an experienced man will get quite good work out of it when nothing better is available.

It is impossible in any known form of furnace to heat up articles of varying cross-section at the same rate throughout their mass. When this limitation is considered in conjunction with the critical contraction changes described on p. 40, it will be seen that permanent distortions of considerable magnitude are unavoidable, quite apart from any question of sagging due to the weight of the object or its position in the furnace. In these days when cutters and noiseless gears have been made almost mathematically exact, no possible source of error can be overlooked. A distortion which is very obvious after quenching or even a crack may be due originally to the effects of critical contraction during heating.

HARDENING TEMPERATURES.

The minimum temperature at which hardness can be conferred on a piece of steel by sudden cooling may be sharply determined by means of the apparatus described on p. 140, in the form of a curve like Fig. 24. Useful as this information is, it must not be assumed that the best results will necessarily be attained by quenching out after heating the tool to a temperature not more than a few degrees beyond the minimum. Both the degree of hardness and the depth to which it penetrates might vary considerably in two tools, one of which was quenched from the

theoretical minimum indicated by the curve, and the other from a temperature, say, 30° C. higher. For several reasons the information afforded by the thermal curve should not be followed blindly.

(1) The temperature at which the critical change occurs varies slightly with the rate of heating, and consequently with the size of the object heated.

(2) The critical change, though no longer appreciable to our apparatus, is probably not quite completed as soon as the heating curve assumes its former course.

(3) The rate of cooling at the beginning of the quenching operation is not so rapid as it subsequently becomes (see Fig. 29), and therefore, in order that the maximum rate may be attained by the time the critical range is reached, the cooling should be started somewhat above it.

In order to avoid any uncertainty in these respects the steel should be heated some twenty to forty degrees higher than appears theoretically necessary. At this temperature the structural transformations take place quickly and completely.

FALLING HEATS.

The usual works practice is to quench out the steel from the highest heat attained; but there need be no hurry about it, as the temperature has still a long way to fall before it passes the lowest point at which the steel will harden (R in Fig. 24). Many operators hold the steel in the air for a few seconds before quenching; this is the meaning of the expression "hardening on a falling heat." There is no harm done by this delay so long as inequalities in temperature in different parts of the tool do not arise, as they certainly would if the range of temperatures through which the tool was so cooled were extended. On the other hand, there is a decided advantage in permitting the temperature of the steel to fall as low as practicable, and contract in doing so before quenching. From these considerations has arisen in recent years a practice which mimimizes the risk of breakage with complicated tools, and generally decreases the brittleness of a tool without, at the same time, decreasing its hardness. This consists in taking the tool already heated in one furnace to the required maximum temperature—say, 780° C.—and placing it into a

second furnace in which it is maintained at a temperature some 10 to 20° C. above the minimum cooling change point, say, 710° to 720° C. As a second furnace the most convenient form is a salt bath, whose temperature can be easily maintained at a quite negligible cost by the heat of the objects constantly being added at a higher temperature than that at which they are withdrawn. Other features of the salt bath furnace, relative to the above purpose, are discussed on p. 94.

METCALF'S TEST.

The following means of determining in an ordinary smith's hearth the degree of redness, at which the finest-looking fracture is induced in steel by quenching, is generally attributed to Metcalf. A bar of the steel being used of about one-half inch diameter is notched for a length of three or four inches, each eight or ten millimetres from one end. The notched portion is then heated in the smith's fire until the extreme end is white-hot, and in such a manner that the heat tapers gradually backwards. After quenching, the bar is dried and broken at each successive notch. The first piece or two will break off very easily—if they do not break in quenching—and exhibit a coarse, staring white fracture. Subsequent pieces will break off less readily, and become gradually finer until the smooth amorphous appearance of well-hardened steel with a faint, bluish-grey tinge is reached. After that the fracture gets coarser down to the unhardened part.

The point about this test, which is usually emphasized, is to observe and keep in mind the precise kind of red colour which existed in the hot bar just at the spot where the best fracture was later discovered. This takes some doing. Moreover, as the precise kind of cherry-red colour, even if it had been observed, would be a reliable guide for future use only under exactly the same conditions of lighting, etc., the value of the test is obviously more apparent than real. The test is, however, of great use in that it provides with little trouble a series of fractures representing the effect of overheating. These may be preserved in a small glass-topped box, such as is used by entomologists, and serve a very useful purpose as standards for comparison with the fracture of defective tools. In this way

the hardener may convince himself of many unsuspected cases of overheating, although it should at the same time be remembered that the degree of granulation in a fracture depends not alone on the temperature, but also on the length of time during which the steel was exposed to it.

ALLING'S TEST.

A modification of the Metcalf test has been described by George W. Alling. It is not as easily carried out as the Metcalf test, but it is in some ways more instructive.

FIG. 27.

Place the steel (a piece about 4″ × 1¼″ square is a convenient size) in the jaws of a milling machine, in such a position that the saw of the machine will cut nearly quarter through at one end, and about three-quarters through at the other. Then round the corners of the groove, and cut out the bottom to a "V" shape. Now submit the piece to a tapering heat, as in the Metcalf test, taking care that the overheating is done on the end least penetrated by the saw,

and, after quenching, wipe perfectly dry. If a wedge is now placed in the groove, and bears on its edge the whole of its length, the two halves can be forced apart by a few smart blows, exposing a fracture, showing the effect of the varying temperatures to which the steel has been heated. A photo of pieces of steel prepared and fractured in this way is reproduced in Fig. 27.

JUDGING TEMPERATURES.

In the absence of any special means of determining and controlling the correct hardening heat, the most uniformly reliable practice is to keep handy a few half-inch bars of the steel being used, and by trial with these to fix afresh in the mind the required shade of redness as often as the conditions affecting colour may change. After quenching the bars are tested with a file and fractured with a hand hammer on the anvil. The method at best is only a makeshift, but if the man using it possesses patience and the faculty of observation, together with a fair share of gumption, he need make no howling mistakes as far as temperatures are concerned at any rate.

The minimum temperature at which a piece of ordinary, say, one per cent. carbon steel can be hardened is about 740° C. If the steel contains two or three per cent. chromium, or three or four per cent. tungsten (magnet steel), the minimum hardening temperature will be 790°–800° C. If heated beyond these temperatures the steel can be cooled to 700°–710° C., and will still harden on quenching (see Fig. 24). We may thus utilize two pieces of steel to fix three points, 700°, 750°, and 800° C. in the temperature range, which is the most suitable for the hardening of ordinary tool steel. The small strips used for cutlery purposes or small files are a handy form in which to use the steel. Cut off pieces two or three inches long, lay them in the hardening furnace, and when they have attained the heat of the furnace quench them out. If the chromium steel hardens, the temperature is 800° C. or over; if the carbon steel hardens and the chromium steel does not, the temperature is not 800° C., but is at least 740° C. If the carbon steel is purposely made much hotter, and allowed to cool to the temperature of the hardening furnace, and on quenching it is found to harden, whereas a

piece heated only to the temperature of the furnace does not harden on quenching, then the temperature is 700° C. or over, but not 750° C. These observations are merely intended to suggest that means of controlling temperatures do not necessarily involve any special outfit.

QUENCHING. Uniformity in the rate of cooling is quite as important as uniformity in the rate of heating of the different parts. But it is very much more difficult to attain, and often impossible on account of the rapid rate at which cooling must take place in order to harden steel at all. There is endless scope for resourcefulness and ingenuity in the quenching operation, and it is unlikely that men who are not disposed to frequent experiment will ever be able to harden successfully very varied and delicate tools.

Almost any desired result can be obtained by quenching in water. It may be quite cold when the tool is simple in shape and required to be glass hard, but for a less intense effect or more intricate tools it may be heated to 30° or even 40° C. If, however, the water be previously saturated with calcium chloride, which raises the boiling-point very considerably, the bath may, if required, be heated to 70° or 80° C. In this way every advantage of oil-hardening may be obtained, and others which are not obtainable with oil, although for the sake of convenience oil is generally preferred. The physical properties of solutions of calcium chloride of importance in this connection are contained in Fig. 28.

QUENCHING LIQUIDS. The properties of liquids which appear to have an influence on their use as quenching media are: *conductivity*, which effects a more or less rapid change of heat between different parts of the bath; *volatility*, which determines the rate of formation of vapour about the steel; *viscosity*, which controls motion amongst different parts of the liquid, and has a good deal to do with uniform cooling; *specific heat*, which is a measure of the amount of heat that can be absorbed by any volume of fluid in raising its temperature through a given number of degrees; and in oils, the readiness with which a coating of charred oil is formed about large objects which do not cool very rapidly. According to Carl Benedicks,[1] the cooling property of a liquid is chiefly

[1] Carnegie Researches, 1908. *J. I. & S. I.*

dependent on a high latent heat of vaporization ; the specific heat, conductivity, and viscosity being of secondary importance. These views, however, at present appear to rest entirely on laboratory experiments, and as they do not entirely fit in with the notions of practical workmen, it seems desirable that they should be confirmed by various forms of mechanical tests made on specimens of various dimensions prepared under practical working conditions.

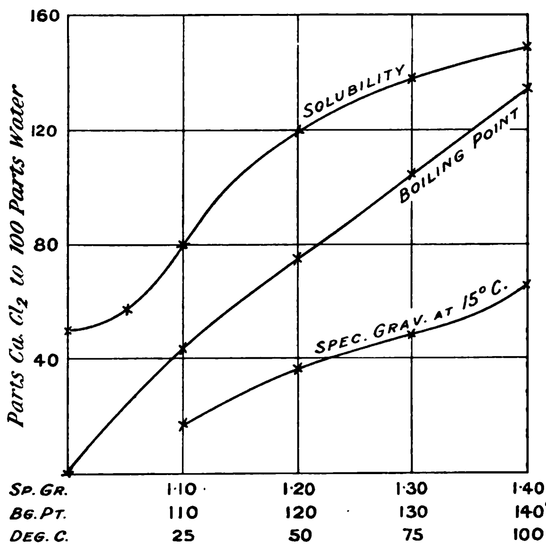


FIG. 28.—Physical properties of solutions of calcium chloride.

SUPERSTITIONS.

It is not intended in the last sentence to convey the idea that any statement at variance with the views of the hardening shop is probably wrong. Although by dint of careful observation and experiment, the hardener's handicraft was well developed before any scientific explanations of it or aids to it were available, it must be said that it has to its account a number of almost incredible notions, which to some extent are still adhered to. A certain amount of superstition may of course always be expected to gather around processes which are secretly operated. Amongst what we may call the ancient literature of this subject, we find, for example, that the urine of a red-haired boy was considered an essential constituent of a first-rate hardening

fluid (see note, p. 145). As ridiculous as this may appear, it is but an illustration of the belief, not entirely abandoned, that some virtue from the fluid in which it is quenched passes into the hardened steel. How many tubs of precious (?) fluid have passed from father to son on this account? It is said that some barrels of Sheffield water were at one time shipped to America for steel-hardening purposes. The report may be unfounded, but a belief has existed amongst Sheffield cutlers for ages long that the water they use is superior to any other for hardening. Precisely the same view is taken by the cutlers of Solingen of the water used for hardening their blades.

MEASURING RATE OF COOLING.

These and similar vain beliefs in specific fluids were considerably disturbed by Le Chatelier.[1] He heated small cylinders of iron into which a thermo-couple was placed and plugged about with clay. On quenching these in various fluids he observed the relative times required to cool from 700° to 100° C. The results as plotted in curves by Haedicke[2] are reproduced in Fig. 29.

The most unexpected result was given by quicksilver (curve B). Its high conductivity, which causes the sensation of cold when touched by the finger, is responsible for the notion that it must therefore cool heated steels very quickly, and confer on them a special degree of hardness. It appears, however, to be distinctly inferior in this respect to cold water, the reason being that the specific heat of quicksilver is about thirty times less than that of water. The cooling effects of brine and dilute sulphuric acid were found to be not appreciably different from ordinary water, and do not bear out the popular notion of their value as cooling agents. The effect of heating the water up to 50° C. is also not very striking, but it must be remembered that these trials were all made on small pieces of metal weighing barely one and a half ounces.

OIL HARDENING.

From a former survey of the physical changes to which the phenomenon of hardening is due, we know that the rate of cooling fixes the degree of hardness attainable, and with the degree of hardness the change of volume and the

[1] *Revue de Métallurgie*, September, 1904.

[2] Haedicke, *Stahl und Eisen*, 1904, p. 1239.

consequent strain also varies. We know also from a consideration of thermal curves that the hardening effect conferred by quenching is confined to a somewhat narrow range of temperature, usually between 720° and 680° C. Cooling below 680° C., however rapidly performed, does not harden the steel, but it prevents the tempering reaction which, if it were not suppressed, would make the steel

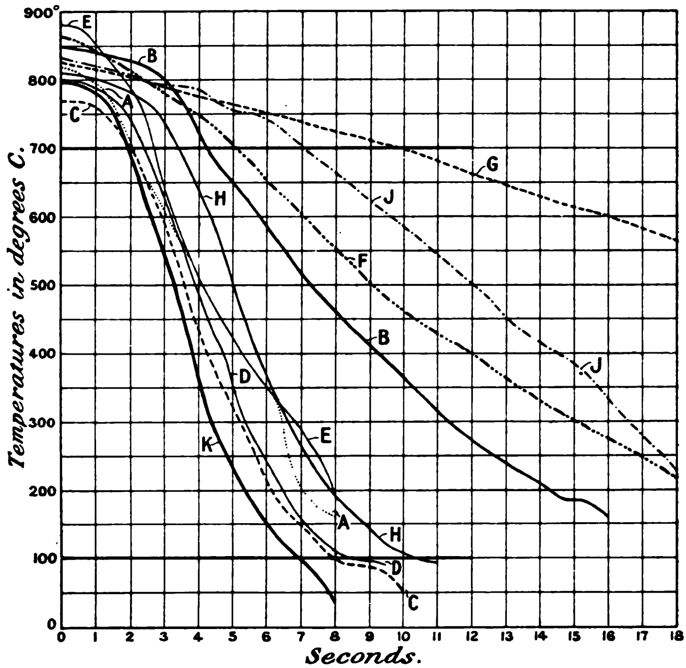


FIG. 29.—Relative rate of cooling in various liquids.

B, Quicksilver. C, Water at 20° C.
D, Salt water. E, 10 per cent. sulphuric acid.
F, Linseed oil. G, Lead.
H, Water at 50° C. J, Water at 100° C.
K, Water spray.

quite soft again. In using oils and similar fluids as quenching media, both the cooling down to 680° C. and the cooling below that temperature take place at a slower rate than if water were used, with advantage or disadvantage according to circumstances. It is obvious that a certain minimum rate of cooling between 720° and 680° C. is necessary in order to harden any particular piece of steel to a required

degree. This rate, however, varies with the composition of the steel, and nearly all high-class crucible steel which has not been especially made for oil-hardening does not harden very well in oil. To use a harder steel on this account for the same purpose does not help very much, as it does not cool more quickly, and the change in the state of the carbon proceeds at about the same rate. If, however, the amount of manganese (0·15 to 0·25 per cent.) usually present in high-quality tool steel is raised to 0·40 per cent. or over, the rate at which the critical thermal change takes place is decreased, and a tool otherwise too soft will harden satisfactorily.[1]

LIQUID MIXTURES.

Of the oils in use, according to Thallner,[2] petroleum hardens with greatest intensity; next glycerine, which has heretofore not been sufficiently appreciated as a hardening fluid; then light mineral oils; and finally viscid vegetable oils, for instance, linseed oil. A layer of oil on the surface of water enables a higher degree of hardness to be attained than with oil alone, and a lesser degree of hardness than with water alone. A coating of the oil forms around the tool as it passes through it and retards the cooling effects of the water. The results can be varied by altering the thickness of the layer of oil, but it needs an experienced man, handling comparatively simple tools, to get uniformly good results. With a similar object the water is sometimes mixed with lime or clay, or even soap, all of which tend to form a thin layer of non-conductive material about the steel. A saturated solution of salt is a favourite mixture; its use by file-hardeners is universal, and in some cases quite necessary in order to keep the water fresh. Caustic soda, sulphuric acid, sal ammoniac, sodium carbonate, manganous sulphate, and practically every soluble substance which comes within reach of the hardening shop has been added at one time or another to the hardening

[1] The question of composition in relation to the hardening properties of tools opens up an extensive inquiry quite beyond the scope of our object, and is more the business of the steel-works than the tool-room. Very little consideration is needed, however, to show that in this respect the co-operation of the user, however familar he may be with "tempers," and the maker of the steel is highly desirable.

[2] "Tool Steel," p. 102.

water. These casual additions do little or no harm, and are not costly; they are, however, generally useless.

QUENCHING IN MOLTEN ALLOYS.

As the hardening effect is over as soon as the temperature throughout has been reduced below 680° C., and the rate of subsequent cooling modifies only the tempering effect, it should be possible to arrange the quenching operation in such a manner that hardening and tempering could be accomplished in one and the same liquid. If, for example, it were desired to temper a hardened object back to 350° C., it might be thought that direct quenching in molten lead at that temperature would be equally effective as first hardening in water and then tempering. And so it would if the rate of cooling in the first instance from the quenching temperature down to 350° C. were as rapid in lead as in water. As a matter of fact it is very much slower, and the use of lead or any similar metal, or alloy, or other heated substance is practicable only in comparatively few cases where great toughness and a very moderate degree of hardness is sufficient; in such cases, however, it is both simple and safe.

PRESS HARDENING.

Very much akin to the metal bath is the use of a press for hardening saw blades, band saws, safety razor blades, umbrella ribs, and other articles of thin section. An idea of the general arrangement of such a press[1] is given in Fig. 30, in which *a* and *b* are hollow metal boxes, that can be cooled or heated as desired by circulating water or hot oil through them. The objects to be hardened are pressed, direct from the furnace, between the plates, and when taken out need no tempering, and only rarely require straightening. By grooving the surfaces of the hardening plates any portion of an object—say the back of a hack-saw blade—may be left soft. This kind of press can also be used for hardening coils of thin band steel. For this purpose it is arranged immediately behind the heating furnace into which the coil unwinds. The steel is then pulled through the hardening plates, which are previously adjusted to such a temperature and pressure that the band leaves them with the required degree of elasticity. The same object may

[1] Mayers' patent in use at the Remscheid Technical School. Haedicke, *Stahl und Eisen*, 1896, p. 900.

obviously be accomplished by means of rolls instead of parallel plates.[1]

How to quench. Very little in the way of general instructions can be given, presuming the tool has been properly heated, as to the manner in which it should be brought into the hardening liquid. If it has not been properly heated, no amount of tinkering at the bosh can make up the deficiency; it had better be re-annealed and given a fresh start. Each special form of tool requires individual consideration, and perhaps

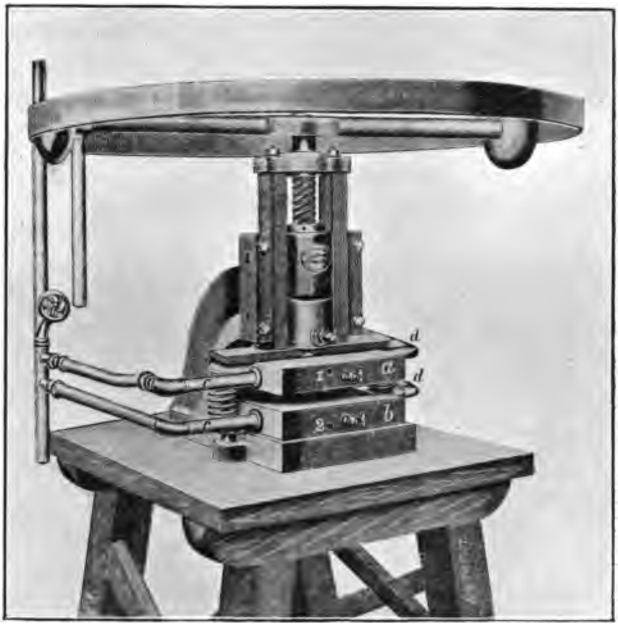


FIG. 30.—Press for hardening thin sheets and strips.

a few preliminary trials in order to arrive at the mode of cooling least likely to originate dangerous stresses and strains. Great variation in the thickness of the adjacent parts, sharp corners and especially sharp angles are always apt to cause trouble. In this respect the machinist or tool designer and hardener must work together.

The thicker parts of an object should always be the first to touch the water, in order that the force of their contraction may be exerted on the thinner sections whilst they are

[1] Huntsman Patent, 5781, A.D. 1909.

still warm and able to bend without breaking. It is also advisable to quench all partially heated tools cold end first.

A simple flat bar, if heated uniformly and quenched by steady immersion of a portion only of its length, will invariably be weakened along the sharp line dividing the hardened from the unhardened portion. If the steel is very hard it will frequently crack along the dividing-line either before or soon after removing from the water; or the weakness may not be discovered until the subsequent grinding starts a small crack.

SOFT SPOTS.

A soft spot on the surface of a hardened object is apt to splinter or even cause a deep crack. Such cracks may be originated by handling with cold or wet tongs, by contact with an unevenly heated furnace bottom, by an accidental splash of water, or by being momentarily laid on some cool surface during transit from the furnace to the hardening tank. However such local coolings may arise, if the heat falls below the critical cooling temperature, the area affected will remain soft or harden imperfectly. Consider now the conditions which may lead to the actual rupture. The surface of the object in the hardened state is permanently expanded; the soft portion is not so expanded and must therefore, so long as it remains a continuous part of the surface, be in a state of tension and actually somewhat stretched. Any sudden shock or molecular disturbance such as grinding, might cause the tension to overstep the resistance of the softer portion, which, being now free, would contract on itself and leave a distinct break in the surface. An instance of this kind occurring on the surface of a case-hardened disc is shown in Fig. 31, which also, by the file marks, illustrates the relative softness of the splintered portion. Splinters of this kind are generally thicker in the centre, and taper off to a very thin edge; they are also hard on the under side. If a section is made through the splinter and properly prepared for microscopic examination, it is usually quite easy to trace its origin back to one or another of the causes mentioned.

Soft spots may be due to actual decarbonization as explained on page 17, but they are then very irregular in shape, and not easily confused with those considered in

the previous paragraph. They may also be caused by heating the tool in a coal fire which has not first been allowed to burn through. In this case sulphur fumes from the coal combine with the iron, and either form a sulphide of iron, or cause the surface to scale very readily and pit. On this account coke or preferably charcoal, if it is plentiful, is the best kind of solid fuel for hardening furnaces. Whereas the soft spots mentioned in the last paragraph disappear on rehardening, those caused by decarbonization do not, but at the same time they rarely if ever cause splintering.

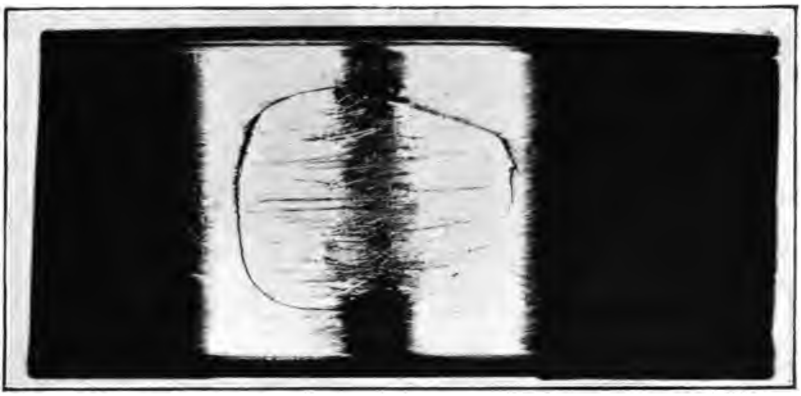


FIG. 31.—Crack on the outer surface of a ring, caused by a soft spot.

SHARP ANGLES.

The most common cause of cracked tools in a well-regulated hardening shop is sharp angles or corners. However carefully the heating may be done, it cannot overcome the inherent danger; the only remedy is to replace them with fillets and rounded corners of as large a curvature as possible. If sharp angles are unavoidable the danger may be minimized by filling them with putty, or a mixture of burnt and fresh fireclay made into a paste with soapy water, or sodium silicate. It is also sometimes advisable to reduce the heat of a fillet itself below the hardening temperature by laying in a strand of wetted asbestos for a few seconds before quenching. A well-rounded fillet is, however, better than a great deal of asbestos string, and these other precautions can also be used if necessary.

The special danger of sharp angles and corners is due to the manner in which cooling takes place about them. Fig. 32 represents the cooling effect from two inner surfaces

FIG. 32.—Location of hardening stresses about sharp angles.

(a keyway) at right angles to each other with the unavoidable line of weakness running diagonally between them. Fig. 33 is a photograph of stibnite (sulphide of antimony) which was cooled from the molten state in a square mould. It

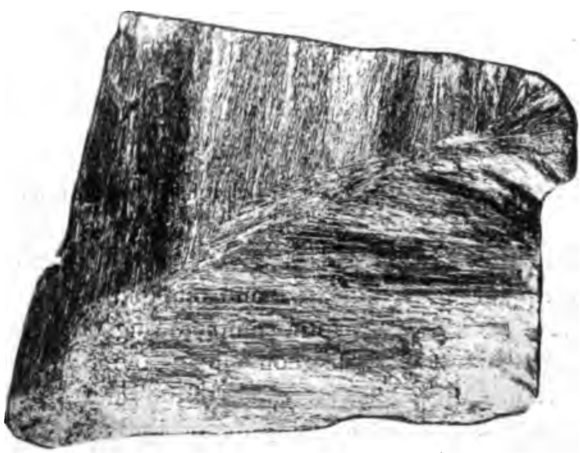


FIG. 33.—Cooling stresses in stibnite.

can easily be broken in the hands along the plainly marked diagonal line. A similar appearance is very marked in topped ingots of mild steel which have been "scorched."

Such ingots, unless very carefully handled, forge into bars with cracked corners; they are also apt to clink in the reheating furnace.

SHARP CORNERS.

We have already referred to the tendency of steel to fracture along a line sharply dividing the hardened from the unhardened portion of a bar. If the section is sufficiently large there is always some point in the interior of a bar where this condition, to some extent, prevails. It is particularly objectionable where surfaces meet to form a sharp corner, and special precautions must be taken with very hard

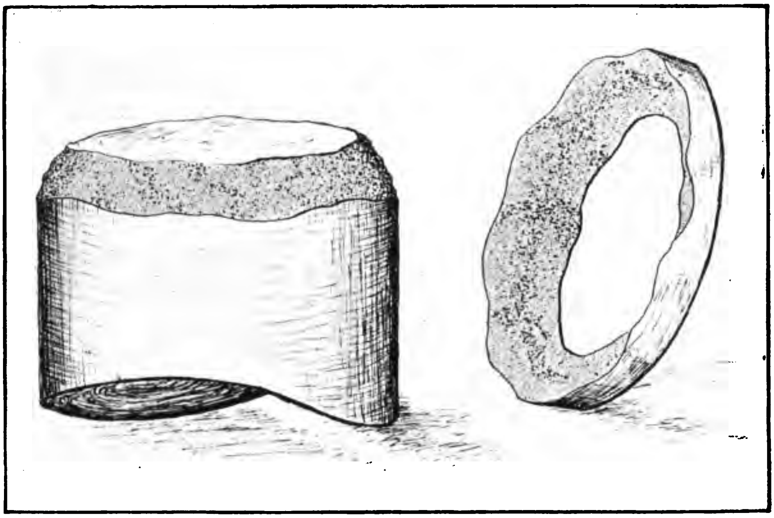
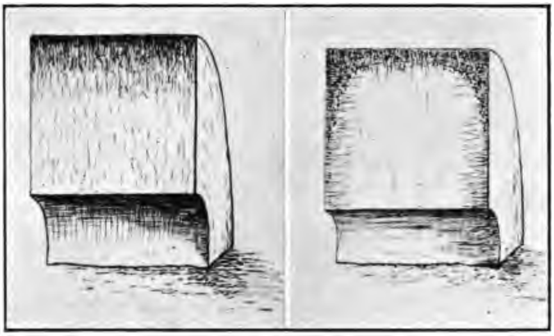


FIG. 34.—Hardening crack around sharp edge due to cooling in directions at right angles to each other.

steels to prevent actual breakage. A round bar of tool steel with flat ends if heated and plunged in water may shed the edges in the form of a complete ring (see Fig. 34).

A great many solid gudgeon pins of the kind formerly used have met this fate. Here, again, the safest way out of the difficulty would be to modify the design. If that is not possible, and only either the round surface or the end requires to be hardened, then the rapid cooling should be confined to these surfaces; this can be accomplished by means of a spray arranged to strike the end, only, or the curved surface.

Similar considerations account for the flaking of hammer faces, and the corners of roll turners' tools. If overheating and irregular distributions of heat are added to the inherent



FIGS. 35*a* and 35*b*.—Two ways of arranging cooling stresses in the teeth of cutters.

danger, then little short of a miracle can avert failure. The circular fracture with which the teeth of milling cutters sometimes break off is due to a similar cause, and may be avoided by laying a circular plate, extending beyond the teeth, on each side of the cutter, so that the cooling may operate only at right angles to the axis of the cutter and produce an even depth of hardness across the width (Fig. 35*a*), instead of a curved line dividing the hardened from the unhardened portions, as in Fig. 35*b*. Cracks of the kind referred to are illustrated in Fig. 35*c* on the teeth of an actual cutter.

FIG. 35*c*.

VII

TEMPERING AND STRAIGHTENING

THE object of tempering may be either to avoid hardening cracks, or to reduce brittleness to a degree compatible with certain mechanical processes. That tempering may, under certain circumstances, originate cracks, is a proposition not readily accepted, but that it actually does so is suggested on p. 76.

TEMPERING COLOURS.

Although a comparison of the actual temperatures to which "dark red," "cherry red," "bright cherry," and so on are supposed to correspond will show variations amounting to 100° C. or more, there is on the other hand a fair agreement between authorities as to the temperature at which the different colours appear when a piece of bright steel is heated. The following are the figures usually given in the text-books, journals and engineering pocket books :—

Colours	Temperatures.
Light straw	220° to 230° C.
Dark „	240° C.
Yellowish-brown	255° C.
Reddish-brown	265° C.
Purple	275° C.
Violet	285° C.
Cornflower-blue	295° C.
Pale blue	310° to 315° C.
Sea-green (or grey) . . .	330° C.

It is, however, erroneous to suppose, as is general, that these colours reliably represent certain fixed temperatures. It is doubtful even whether they represent definite degrees of tempering. Opinion is divided on this latter point.

TIME ELEMENT.

If a piece of polished steel weighing, say, five grams were placed in a vessel previously heated and kept at 275° C. it

would become yellow after two minutes and pass through every colour up to light blue in about half an hour. In this way, similar pieces of steel were heated with free access of air at varying temperatures with the following results, the figures being minutes required to produce the full colour stated at the head of the vertical columns :—

Temperature.	Straw.	Brown.	Purple.	Dark blue.	Pale blue
200° C.	6	49	—	—	—
220° C.	3	33	63	—	—
250° C.	1	10	39	—	—
275° C.	½	3	11	27	40

From these results it appears that if the tempering effect —not the colour—depends on the temperature, and is mostly independent of the time, then the colour is of value only as an empirical guide under definite conditions. It has been said that the result is the same, in respect to both hardness and other properties, whether the colour is obtained by a shorter heating at a higher temperature, or a longer heating at a lower one. This, to say the least, is a very doubtful conclusion, and is certainly not borne out by mechanical tests on oil-hardened and tempered motor-car steels, which, after tempering for periods varying from fifteen minutes to two hours, do not show very great differences.

The temper colour, as was shown by Humphry Davy in 1813 or earlier, is due to surface oxidation,[1] and it might be expected to change in colour with time independently of increased temperature, just as scale formed at red heat increases in thickness in time, although the temperature remains constant. Under such conditions, both the temper colour in the lower ranges and the scale formed above red heat may be very misleading temperature indicators. It would, however, be generally conceded that the actual temperature, and not the incidental thickness or colour of the scale determined the extent to which certain physical

[1] See paper by Turner (*Chem. News*, 1889, vol. 60, p. 190), who says, "A purple can be produced at 250° C. in a few minutes, which would require an hour at 220°, and about twelve hours at 170°, though the ultimate result would be the same in each case.

changes had taken place. The rate at which the colours are formed at any fixed temperature is increased locally about any portion of a piece in actual contact with another metal; say the end of a naked thermo-couple.

TRADE CONSIDERATIONS.

In certain branches of trade, tools come on to the market "blue-finished" and would hardly be saleable otherwise. For such reasons, and in view of its general convenience, the temper colour is likely to continue, and may even be recommended under definite conditions, to decide when the required degree of tempering has been reached. It is also quite indispensable under some circumstances in hardening simple forms of tools which, after being partially quenched, are rapidly brightened and allowed to run back with the inside heat until the selected colour appears.

OIL AND LEAD BATHS.

For accurate work, however, colour indications are decidedly inferior to an oil bath which can be maintained for any length of time at a fixed temperature. Articles heated in oil can be raised to the same uniform temperature throughout, which is a consideration of some importance. For higher temperatures a lead bath may be used, and, in the form of a rectangular trough, is especially suitable for tempering long blades. Lead is also used everywhere for tempering file tangs, drill shanks, and other parts of tools which require to be locally softened. The lead bath can easily be kept slightly above its melting point (327° C.) by observing the crust of metal which forms on the sides of the trough. The bath can be kept fluid at lower temperatures by adding tin in the following proportion:—

Per cent. tin . .	10	20	30	40	50	60
Fluid at . . .	300°	275°	255°	230°	210°	185° C.

Or by adding antimony (which is cheaper than tin) in the following proportions:—

Per cent. antimony	5	10	13
Fluid at	290°	270°	250° C.

Higher temperatures are roughly controlled by the charring (300) or sparking (430) of a strip of pinewood, or the rate at which temper colours form and creep up the length of a bright steel bar immersed vertically in the bath. All these methods are inferior to actual pyrometric

measurements, but often sufficiently accurate and much more practicable.

OIL FLARING.

Small articles which are manufactured in large quantities are sometimes tempered after oil-hardening by heating until the adhering oil flares or its flame dies down. This method cannot be commended if the pieces are of irregular thickness, because the thinner parts are more quickly heated to a higher temperature. In other cases, with split washers for example, the method appears to give excellent results. It is generally called for when temperatures beyond the safe usage of oil are required.

It sometimes accidentally happens that a steel suitable for turning tools or small drills gets made up into machine taps or some such tool required to withstand rough usage. With the usual degree of tempering they are too brittle; and appear too brittle after further tempering until they become too soft to keep a cutting edge. This brittleness is caused by free cementite, which is not effected by tempering, though the net brittleness decreases, and finally the mass of material can neither cut itself nor hold the cementite particles up to the work. The remedy is to choose a milder steel and temper it to a less degree.

The table on page 60 is usually accompanied, in an additional column on the right hand, with a list of tools which should be tempered to the respective colours. Such lists are apt to be misleading, unless the kind of steel used, the size of the tool, the manner of hardening it, and the precise kind of work for which it will be used are specified. Every machinist prefers the most durable tool he can get, and on that account draws the temper no more than may be necessary, and as often as not to some colour quite different to the one stated in the usual list. In the matter of tempering, a few trials under working conditions are always more satisfactory than a stereotyped procedure taken from a book or a catalogue. The latter method will always give passable results, but a long way below the best results obtainable. If during the tempering operation the object has also to be straightened, then the temperatures used may have to be increased beyond what would otherwise be necessary.

STRAIGHTENING.

Warping in tools may be due either to want of uniformity

in mechanical structure, or rate of heating or cooling. Those due to mechanical strains (Fig. 16) or irregular forging, can be improved by annealing and slow cooling; those due to irregular heating or cooling must be remedied if they cannot be avoided, and frequently the former is found least troublesome in the long run.

SETTING TOOLS.

In tools of irregular thickness, but symmetrical cross-section, warping may be almost eliminated by setting the tool out of the straight in such a manner that quenching always pulls it back again. The handling of a long sword blade may be cited by way of illustration. The blade, which has been already annealed to remove forging and rolling strains, is heated to redness in a salt bath or on the hearth of a long furnace. It is then brought out on to a metal table where, the point being held in a slot, the entire blade is bent about its back edge to a fixed template. The template is constructed of such a form as experience has shown will bring the blade out straight with a certain method of quenching, which is purposely made as simple as possible, so that it can be easily repeated any number of times without deviation. All half-round files are set before hardening, and then straightened slightly if necessary after quenching, but before they are quite cold. For this purpose a pair of iron bars are fixed at a convenient distance apart on the top of the tank, the file is strained in the required direction between them, and water is thrown on the upper side of the file to make it quite cold before the stress is relieved.

SPECIAL SHAPES.

Steel sheets, such as saw blades, are best hardened if possible in a press (Fig. 30), which keeps them so straight that very little, if any, smithing is required. After direct quenching most of the buckling can be taken out by passing them between the polished flat surfaces of a press, which are heated to the required tempering temperature. The final straightening is then done with a hammer, the length of whose rounded face runs nearly parallel to the shaft, in a manner which, though apparently simple, requires great skill in order that each blow may actually straighten and not make the steel more crooked. Each blow is intended to stretch the concave surface of the steel, and is made to do

so in the required direction by varying the direction of the indent made by the hammer face. Material which cannot be stretched cannot be straightened by the indent of a hammer face. This means that saws or machine knives, which are made very hard, can be readily cracked in the smithing operation, because the nature of the material does not permit it to extend as much as is required. Small hair cracks on the surface of metal-cutting saws, which become visible only on grinding, or perhaps later, can frequently be traced directly to the indent of the smith's hammer.

Long tools, such as drills and reamers, after being warmed are straightened under a screw press. Long thin blades, such as sword blades, are laid in a slot or a pair of slots, and straightened by means of a claw; *i.e.* a stiff piece of steel with a slit of suitable width at the end. A couple of claws may sometimes be used to straighten a blade by twisting each end in opposite directions, the blade having, of course, been previously brought to the required tempering heat; or one end may be clamped in a vice. Every precaution should be taken to avoid warping in the first instance, as a straightened article will more easily run out of truth at any subsequent time under rough usage.

VIII

HARDENING TYPICAL TOOLS

CHISELS, SATES, MILL-PICKS, ETC.

IN hardening such objects as chisels and sates, it is not necessary to heat the entire tool, but merely one or two inches of the pointed end. Too short a portion should not be heated, otherwise the part behind the hardened point may bend under heavy blows, and cause the extreme end which cannot follow the deflection to break. If a great

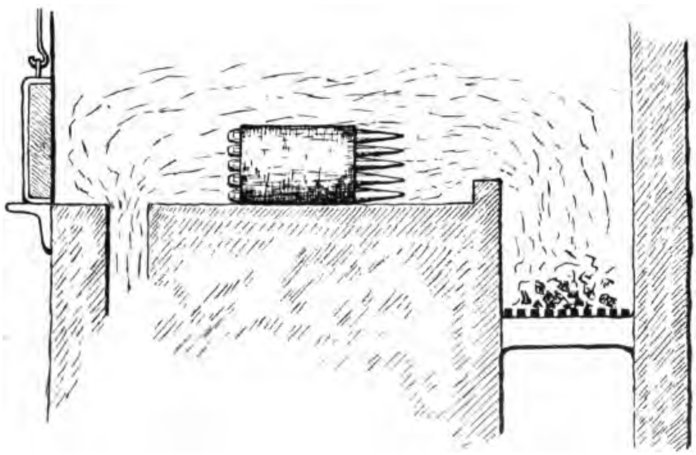


FIG. 36.—Reverberatory hardening furnace.

number of chisels have to be hardened, an ordinary reverberatory hearth, with the heat passing from the fire at one end to the flue against the working door at the other, does very well for heating purposes. The tools may be packed into a short piece of iron piping six or eight inches in diameter, open at both ends, and rolled gradually towards the position on the hearth where the temperature as indicated by "Sentinels," or other means, is beyond 770° C. and not 800° C. (see Fig. 36), or they may be reared in rows

over a piece of one-inch square iron. As the points are towards the fire they only are heated to the required hardening temperature. At small expense the entire batch of tools is prepared for quenching, which operation can be accomplished almost as rapidly as the tools can be conveyed singly from the furnace to the hardening tank.

A salt or lead bath furnace can also be conveniently used for hardening chisels. The latter is especially suited for hardening millpicks, as one end at a time can be easily heated without interfering with the temperature of the other end. Tempering is done by laying the shanks of the chisels across the breadth of a long narrow stove where they are heated up uniformly until the dark blue or some other chosen temper colour appears on the brightened point. A piece of U angle iron heated, either by gas or otherwise, can be readily made into a suitable stove. Hand chisels for chipping very soft materials are sometimes made from steel containing about 0·4 per cent. carbon, in which case they should be hardened from 800° to 820° C., and need not be tempered.

RIVETING SNAPS.

These tools are usually machined direct from the bar. If the steel has a coarse fracture instead of the normally fine one it is unfit for first-rate snaps, and a tool made from it is almost sure to break in the groove, even if the cup stands well. The aim should be to form an even layer of hardened steel immediately behind the face of the cup. Direct quenching would make the edges too hard, and leave the centre of the cup too soft, and the former would tend to fly off in use. The snaps can be well hardened under a tap, as shown in Fig. 37, A, but an equally convenient way is indicated by Fig. 37, B.

The snaps may be heated like chisels in a parcel, and can also be tempered like chisels, or, better still, by placing them shank end first through the perforated cover of a shallow lead bath until the correct temper colour appears.[1] When large quantities are being hardened, a spring clip can be arranged so that the hot snap is held in the correct

[1] Although a temper colour corresponds to different temperatures under different conditions, as stated on p. 60, it answers to the same temperature if the conditions are kept the same.

position over the ascending water-jet, and can be easily knocked out and replaced by its successor.

The life of well-hardened chisels, sates, and snaps, is as often shortened by wear in the head as fracture at the point. This wear is very pronounced if the tools are made from annealed stock. Amongst other ways, it can be avoided by hardening the heads, say in oil, before the

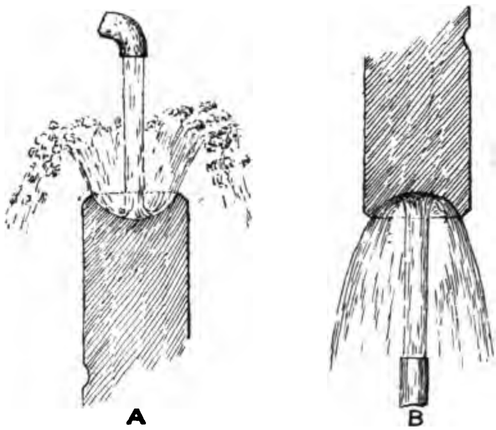


FIG. 37.—Methods of hardening boiler-makers' snaps.

cutting edge is hardened. During the second heating, if carried out as suggested above, the head gets heated only to 600° to 700° C., and when cold has as good an elongation as before but a much higher elastic limit, and hence neither splits nor so readily forms a mushroom head.

TAPS, REAMERS, BROACHES, ETC.

The hardening of taps and such tools as reamers, broaches, and twist drills should bestow on them hard cutting edges to stand up to their work, and comparatively soft flexible cores and flutes so that accidental shocks in a deep hole may not cause them to break off short. This ideal can be approached in two ways. First, by the use of good crucible steel free from non-metallic impurities and low in manganese, which from its nature will permit the hardening effect to penetrate barely beyond the bottom of the teeth; and second, by a mode of quenching which, on account of its general applicability, deserves a detailed description.

BROKEN HARDENING.

In hardening any form of toothed tool, so that the hardening effect barely penetrates to the root of the teeth, we not only prolong the life of the tool, but also mimimize the danger of water cracks. The operation known as "broken hardening" consists in quenching the tool in water until the colour has disappeared from the surface, and then allowing it to stand quietly in oil until it is cold. The heat still remaining in the centre of the tool keeps it soft and penetrates gradually towards the edges of the teeth, but it can at most only slightly temper them up to the heat of the surrounding oil. Tools may be safely hardened in this manner which by quenching outright would frequently crack. Working continuously on the same kind of tool, the operator quickly learns just how long it is best to cool in water, so that after oiling no subsequent tempering is required.

A similar result can be attained in the hardening of reamers, taps, etc., by heating them in a lead or salt bath until the teeth only are red, and then quenching, but the results are not so reliable. It is, of course, much easier to correct warping in tools which are left with the core soft.

MILLING CUTTERS AND ROLLS.

Milling cutters should also be quenched, first in water until the teeth lose their colour, and then in oil. Sharp angles in keyways and at the root of the teeth should be avoided for reasons stated on p. 56. If teeth break off at all they generally do so along half-moon cracks, and either because they have been overheated or badly quenched, or both. Very large cutters may be handled like steel rolls. The following description of the hardening of a steel roll is taken verbatim from Thallner's book.

"The danger of cracking from the interior has been reduced in the construction of the roll by boring it out. The entire surface of the roll *a-a*, *b-b*, Fig. 37*a*, is to be hard, while the journals, *z-z*, are to remain as soft and tough as possible.

"Previous to heating, the journals, *z-z*, are given a coat of loam, or clay, which, to make it more binding, is mixed with cows' hair, and, to prevent peeling off in consequence of shrinkage by heating, with chamotte, graphite, pulverized firebrick, etc. Each journal is enclosed in a sheet-iron pipe

of as large a diameter as the thickest part of the roll, and the mixture rammed in between the pipe and the journal. At *m-m* discs of sheet-iron projecting beyond the edge of the roll are arranged. Finally the bore, the ends of which are provided with screw threads, is up to the latter rammed full of dry loam.

"In heating the roll, which frequently requires several hours, it must be borne in mind that during this time the surface is exposed to the injurious effects of the gases of combustion, as well as to decarbonization, if suitable

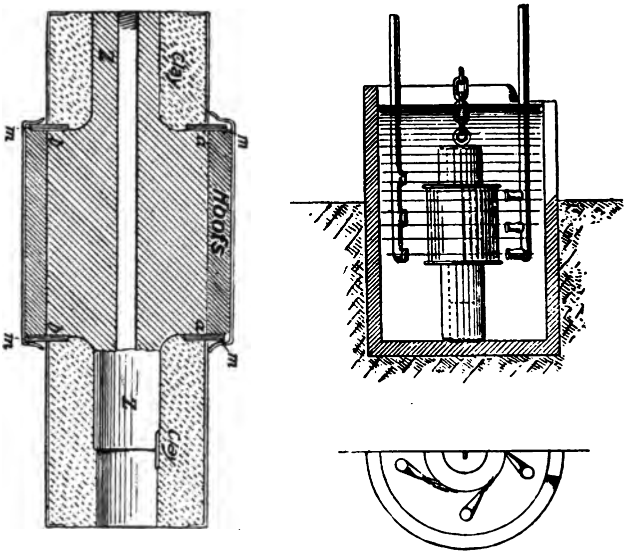


FIG. 37*a*.—Appliance for hardening rolls.

protection is not provided. For this purpose the roll is enclosed in a sheet-iron pipe of somewhat larger diameter, and after the space between the roll and the pipe has been rammed full of hoof-shavings, or charcoal, the edges of the pipe are turned in.

"The roll may now be brought into the least heated part of a reverberatory furnace of sufficient width and allowed slowly to heat. Heating in a reverberatory furnace is preferable, because other appliances, for instance heating with charcoal, are not always available, if the roll has to be turned to attain a uniform temperature. The reverberatory furnace used should have as long a hearth as possible, so

as to cause a heat gradually increasing towards the fire grate. The roll is now gradually rolled into the higher heat and turned, more frequently the hotter it becomes. When the roll is supposed to have acquired the suitable hardening temperature, a hook is screwed in the threads on the end of the journal, and the roll is suspended by it by means of a chain. It is then freed from the sheet-iron discs, which can be readily removed, and quickly cleansed from adhering hoof-shavings with a wire brush. The roll is then plunged into the hardening bath, which should be located near the furnace.

"Since uniform cooling of a roll of large diameter by moving it about in water is impossible, it is allowed to rest whilst the water is brought into vigorous motion. This object is attained by the appliance shown in the illustration. It consists of a vessel of sufficient depth, and of a diameter twice to four times as large as that of the roll, and is provided with pipe conduits for the introduction in a slanting direction of water under pressure.

"The nozzles of the pipes are made broad and slit-shaped, and a number of them are distributed at various heights, so that the water around the roll is set in a vigorously whirling motion. The manner of using this appliance will be readily understood from Fig. 37*a*."

HOLLOW TOOLS.

On tools having a smooth, narrow bore, which require to be hardened, an asbestos washer should be laid after the heating operation, and against this washer should be pressed the flange end of a pipe, delivering a stream of water sufficient to fill the bore. If the bore is wide enough, a piece of gas piping closed at one end and perforated may be passed through the tool so that forcible streams of water, coming through the perforations in the pipe, strike the parts to be hardened. Narrow parts, as, for example, the path in a ball race, may also be spray-hardened, as indicated by Fig. 38.

As ball races are now frequently made from case-hardened mild steel, they are generally quenched outright, either vertically on a hook, or horizontally on a piece of stout wire whose lower end is coiled into a circle round about and at right angles to its length.

RAZORS, TABLE BLADES, AND PEN-KNIVES.

Knife blades are frequently heated in a slow coke or charcoal fire, but a shallow salt bath containing a movable basket is a more ideal arrangement. The heated blades are quenched by being pulled almost horizontally through the water with the thick end first. Razors are not tempered. Table-blades can be tempered in bulk in an oil bath, and pen-blades by laying their backs in molten lead, or on a hot plate, or even, when handled on a small scale, in the flame of a spirit-lamp until a suitable colour runs down to the edge.

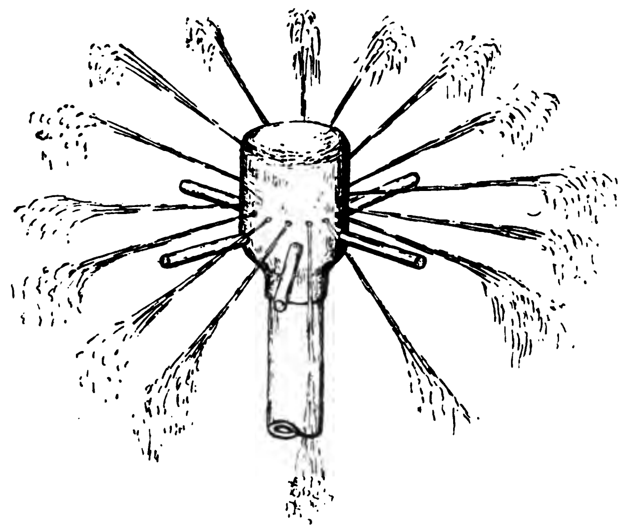


FIG. 38.—Arrangement for hardening the inside of narrow rings.

WIRE AND WATCH-SPRINGS.

Long coils of thin steel are heated for hardening by passing at a suitable rate through a tube which extends between the opposite walls of a furnace. On reaching the exit end the steel should have already reached the hardening temperature, and passes then through an oil-tank, and, subsequently, in a continuous line through a tempering furnace or lead pot, or sometimes first through a pair of brightening rolls, and then through the tempering-tube, so as to give a finished spring the usual blue colour. This operation is similarly applied to wire. If the steel wire is high in manganese and not too thick, it acquires high tensile properties simply on passing from the hardening

furnace through the air on to the coiling machine; but the other mechanical properties of the wire, *i.e.* the elastic limit, reduction of area, etc., are not so good as in material which has been oil-hardened and tempered.

HAMMERS AND ANVILS.

Small hand hammers are heated throughout by any suitable means, taken from the furnace, and drawn with a sharp sweep through the hardening tank. They are then, being still quite red, hung by means of the hole on to a projecting peg so that the lower face is below the surface of the water, and the upper face is in direct line with a smooth stream of water falling from a tap. For special forms, engineers' hammers for example, the round-nosed end may dip into a small hemispherical basin through which fresh water is continually rising, whilst the upper flat face meets a stream of water falling from a tap directly above it. The two faces of small hammers may also be expeditiously hardened separately by heating in a lead bath. Larger hammers can be treated in the same way, but it is economical to pre-heat them somewhat in a reverberatory furnace.

Large sledge hammers are most easily hardened between two horizontal sprays. The heated tool is laid, with the eye standing vertical, on a small metal block between the sprays (Fig. 39). A strong stream of water is suddenly turned on and quickly cools the two faces, whereas the middle of the hammer about the eye remains quite soft: whilst still sufficient heat remains, the water is stopped and the ends of the hammer brightened in time to observe the required temper colour, after which the hammer is cooled outright. Sledge hammers made from mild steel do not require tempering. The faces of a large hammer can be hardened in an ordinary bosh fed with a single water-tap as follows: The heated hammer is gripped firmly about the middle with a pair of tongs, and swung length on through the bosh and back again. One end is then for a few seconds held under the tap whilst the other dips into the water. The hammer is then deftly turned and swung again through the bosh, and again held, but this time with the other end under the tap, and so on, according to its size, the hammer is swung three or four times or more until the faces are nearly cold.

Anvils which require hardening on the face only may

be heated in a lead bath face downwards, then supported, also face downwards, on a grid or across two triangular pieces of steel in the water tank directly over a stream of cold water ascending through a spray. The anvil should be immersed as far as the hardening heat extends, otherwise

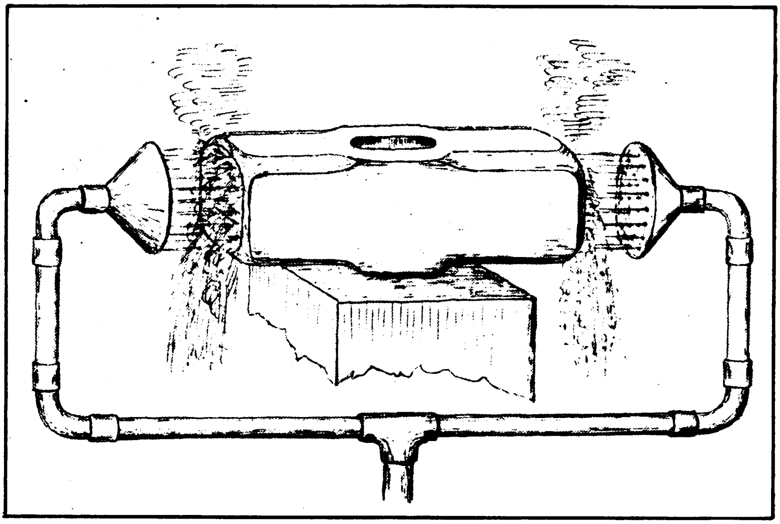


FIG. 39.—Method of hardening sledge hammers.

the corners may crack. The hardened face, if made too thin, will crack and shell under the blows of the hammer. Blacksmiths' anvils and similar flat faces terminating in sharp edges and corners are best hardened with a powerful spray.

DROP-FORGING DIES.

The hardening of drop forging dies for producing intricate objects requires the exercise of considerable experience and more skill than can be assimilated from a written description. In many cases the bane of the steel hardener—sharp angles and corners—cannot be avoided. In all save the simplest forms the die should be withdrawn from the water before it is quite cold, be brightened on the surface, and tempered by the heat still remaining in the massive unquenched back. As a matter of experience certain parts of any particular die will be most disposed to spring off and develop subsequent cracks. It may be necessary to temper these parts to a greater extent by laying on them pieces of heated iron or otherwise. In the same way certain other parts of the die may require additional cooling by the local application of a limited amount of oil or water. If the dies are heated for hardening in a reverberatory or muffle furnace the faces should be covered with charcoal or otherwise protected from oxidation. If this is not done, the extreme surface remains soft though the die is quite hard immediately underneath.

IX

DEFECTIVE TOOLS

IT is easy enough to spin fine theories about the origin of defects in tools, and not altogether a bad thing to do, so long as the theories are taken for what they are until observation and experiment confirm them or otherwise. The characteristics of a broken tool from which the causes must be deduced can generally be neither measured nor weighed, and yet are quite as convincing as absolute figures of quality would be, and much easier to interpret than some kinds of figures are. A quick sense of the meaning of apparent trifles and close observation and comparison of appearances are important for the tool-hardener who would manage the forces he deals with, just as they were for the steel-maker of the last generation but one, who controlled both his raw materials and finished bars by appearances, and thereby to some extent earned the right he exercised as an authority, not only on the manufacture of steel but also on its uses and properties and the causes of failures and defects.

CRACKS.

It is not uncommon to attribute all cracks to overheating or some other abuse of hardening methods. They may, however, be due entirely to the size and shape of the object, or to unsuitable composition of the steel from which they are made. Fig. 40 A and B are intended to represent the appearance of the same kind of steel quenched in each case from the same temperature and varying only in cross sectional area.

A has cooled so rapidly that the characteristic appearance of hardened steel extends throughout. B shows a marked core of unhardened steel. It is evident that a larger section would possess in a still more marked degree a core which, owing to a slower rate of cooling in the interior of the bar,

would not be appreciably harder than a piece of steel as forged.

It may, we think, be presumed that the greater hardness of the exterior portion of a quenched steel bar is accompanied by a greater degree of permanent expansion. From the surface towards the centre the expansion would decrease with the hardness if the interior portions were free to arrange themselves as they chose. They are, however, attached to the hard unyielding and permanently expanded exterior portions, and must therefore remain in a state of tension and actually stretched as long as the hardened object is intact.[1] If, however, the strain should exceed the endurance

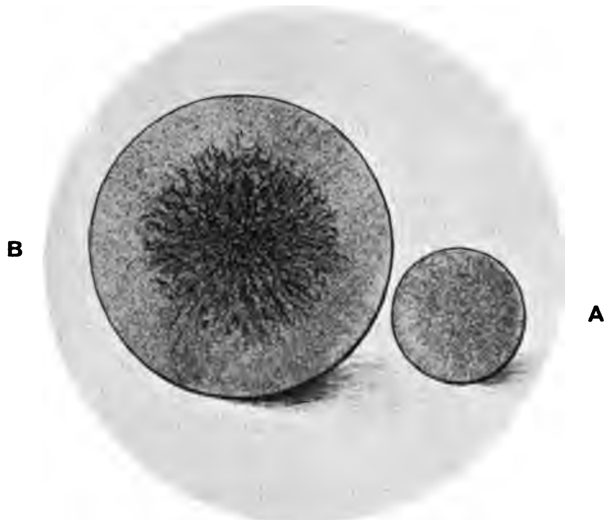


FIG. 40.—Soft core in hardened steel.

of the steel a crack is formed internally, and those steels which are naturally less extensible are the more apt to crack in this manner.

TEMPERING CRACKS.

From the above considerations it is clear that any internal defect in the steel itself, such as a pipe, a crushed

[1] When working on large objects which have to be accurately finished, the machinist frequently finds that the marked dimensions vary appreciably after rough turning; that is to say, after the stressed surface has been removed the internal material is free to assume its normal size.

centre, an imperfectly welded blow-hole or segregation would cause premature fracture very much like a slag streak does in a tensile test-piece cut transversely. It also follows that any change which increases the expansion of the exterior portion without at the same time decreasing its rigidity, increases the strain of the internal portions and may cause them to break apart. In this way a bar which

FIG. 41.—Test pieces cracked by tempering.

in the hardened state was perfectly sound may, on tempering, develop internal cracks unless heated very slowly.[1]

A large number of pieces about one and a half inches square were cut from an annular ring, then turned to one and a half inches round and all hardened and tempered

[1] The phenomenon of "clinking" in large ingots, particularly in those of circular section and hard material, is well known and due to similar causes.

alike in a manner which would be generally considered correct. Every piece appeared perfectly sound after hardening, and some of them also after tempering; but on turning the apparently sound ones to a smaller diameter for testing purposes they also showed longitudinal cracks at right angles to each other. The appearance of the broken pieces is reproduced in Fig. 41, and might easily be considered sufficient evidence of unsound steel.

A similar number of pieces from the same ring were hardened and tempered before turning off the corners, and produced perfect test-pieces free from any sign of cracks. In both series the mechanical properties of the hardened material were practically the same, save the reduction of area, which in the split pieces was naturally much less.

Had the same treatment been given to round bars of the same material whose diameter was much smaller or much larger, the danger of internal cracks either on hardening or tempering would have been more remote.

From the above considerations one might be led to the conclusion that merely so far as sound bars are concerned a degree of overheating, *i.e.* the penetration of the hardening effect and consequent expansion to the centre, might sometimes be advantageous. This statement is not intended to provide an apology for neglect of any kind, but rather to suggest that, with a given material, it may be necessary to consciously depart from an ideal to keep down the percentage of wasters. There are also reasons to suppose that cracking in particular kinds of steel made into special shapes is more apt to occur when hardening is done from certain temperatures than when either higher or lower temperatures are used.

INTERRUPTED COOLING. Partially cooled steel objects will sometimes break on taking from the quenching bath which would remain sound if left in the bath until they were quite cold. Very likely reasons for this behaviour, which is well marked only with objects of certain shapes, are as follows:—

(1) That the inside portion has not yet passed the critical expansion period (see p. 40 and Fig. 26), and this is partly suppressed by keeping the object in the water.

(2) The outside expands under the warmth of the heat diffused from the inside, and so pulls the centre apart.

Under conditions described in (1) the crack would originate on the outside, and under conditions (2) on the inside; if both act together the tool would probably break with explosive violence into several pieces.

GEOMETRICAL CONSIDERATIONS.

The difference may be much less between a bar that cracks and a similar one that does not than the differences which exist amongst a number of uncracked bars. Tools indistinguishable from one another may pass from the shop only one straw or a thousand straws removed from breaking-down point. But the danger of internal flaws, either actual or potential, is always greatest in complete round sections. In the first place, because the strains are symmetrical and all converge on to the centre; and in the second place, because (in tempering) the heat is equally distributed, and the expansion therefore is comparatively large before any portion of the rigid surface is hot enough to become plastic.

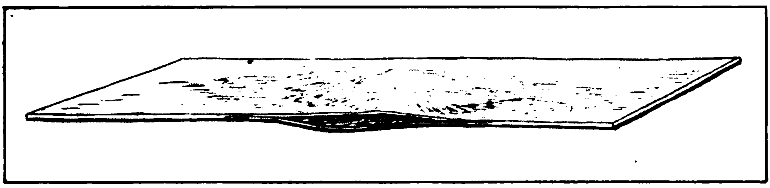


FIG. 42.—Piece of flat steel containing pipe: after hardening.

In a square bar the corners quickly attain the heat of the tempering bath and can yield to internal stresses before the surface expansion produces rupture; moreover, under like conditions the centre of flat surfaces can yield better than any part of a circular section. Flat pieces are still less apt to break in this manner, even if they are very thick, and never if they are thin, unless the steel is defective. Thin blades which are made from sheets or strips containing a pipe, a slag inclusion, or an unwelded blow-hole will frequently open out as indicated by Fig. 42.

STRAIGHT CRACKS.

The kind of path along which a crack travels may be almost conclusive evidence of its origin. No experienced

person would ever suggest that the half-moon or thumb-nail cracks met with in chisels, plane irons, cutter teeth, and so on were due to defective material. They might be due to unsuitable material, overheating, careless quenching, or some other mistake discoverable on closer observation. Cracks of this kind, and practically every other which originate from hardening strains pure and simple, sweep along a smooth path, from the curvature of which some indication of the mode of heating or the manner of quenching can generally be deduced. On the other hand, a crack which forks irregularly, though the effect of overheating or other errors may appear, is usually traceable to free cementite, or cold working, or both.

FIG. 43.—Forked crack following cementite outline (magnified 100 diameters).

FORKED CRACKS.

A crack runs by preference along the path outlined by free cementite because cementite is brittle and offers little resistance; and also because the different degree of expansion of cementite and the material in which it lies embedded favours the origin as well as the extension of a crack. Figs. 43 and 14 are typical examples. In this must also be included such cracks as may originate in, or

traverse the path occupied by, slag inclusions. Microscopic examination and the knowledge of the composition of the steel enables us to detect these causes when they exist. Heavy cold-working through the blue-brittle stage (p. 21) or crushing between rolls or otherwise may originate forked cracks in steel which contains neither slag streaks nor free cementite. They are not usually visible until after hardening, and then appear in many cases on opposite sides of the crushed object, as represented diagrammatically by Fig. 44.

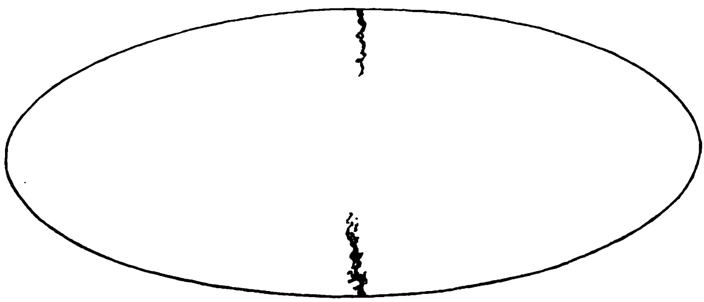


FIG. 44.—Cracks in symmetrical objects due to crushing between rolls.

INVISIBLE CRACKS.

A crack may be so fine as to elude detection at the time the tool is hardened and become visible after lying about for some days or weeks. Such cracks may easily be detected in sand-blasted articles if, before cleaning, they are placed for some hours in oil, or happen to have been oil-tempered, by the oil which has penetrated the crack again oozing out and making a dark stain on the matt-silver surface. On a water-quenched tool, or even an oil-quenched tool which has been cooled off in water after tempering, or subsequently been ground on a whetstone, the crack may be gradually widened by the oxidation of its moist surfaces. As the oxidized metal occupies a larger volume it either presses the faces of the crack apart or forces its way between them on to the surface. Fig. 45 is an example of such a crack originated by cold working in the threaded hole of a boiler-plate firebox, and Fig. 46 a similar crack occurring in an oil-hardened blade.

The nature of the material exuding from such cracks in

oil-hardened steel may be some indication as to whether the crack originated during the quenching or in some subsequent operation.

GRINDING CRACKS.

A piece of quenched steel characterized by great hardness is sometimes spoken of as being "glass hard"; it should be remembered that on the hardest parts it is also nearly as brittle as glass. A brittle object is readily broken because a blow is an effort to change its shape which strains it more in one part than another. But heat also can change the shape of an object, *i.e.* cause it to expand. If a hardened piece of steel in the form of a long rod be

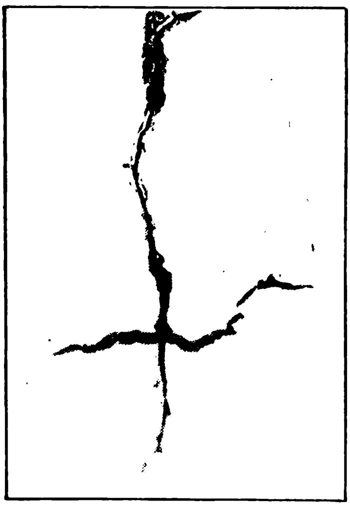


FIG. 45.—Crack in threaded hole of boiler-plate fire-box.

FIG. 46.—Crack on bevelled edge of sword-blade.

clamped at one end in a horizontal position so that its free end rests in front of a divided scale, and the tip of a spirit lamp be brought for a moment under the rod near the clamped end, then the free end, owing to the expansion of the underside, will move up the scale. This experiment[1]

[1] Taken from Ostwald's "Die Schule der Chemie."

shows that a piece of the hardest steel bends *slightly* under the influence of local heating without fracture; but if the heating be strong and the local expansion suddenly great, then the steel, like glass, will crack. This is what may happen when a piece of hardened steel is rashly brought on to a sharp dry emery wheel.

The danger is not so great with ordinary carbon steel, because the rise in temperature is quickly followed by a softening of the material. But high-speed steel remains hard and inflexible at much higher temperatures, and the risk of fracture is therefore greater. In the latter case a small crack once formed readily extends further and deeper if an attempt is made to grind it out on an emery wheel. Cracks can be readily ground out of annealed material, and the steel may be handled in all respects with greater freedom.

OVER-HEATING. It has been said that more tools are spoiled by overheating than all other causes combined. The statement is perhaps a bit exaggerated. It is often so easy to detect overheating, and requires some imagination to discover other errors to which overheating is but contributory. Many young enthusiasts, having spotted a coarse fracture, have heated a tool afresh to a more correct temperature and produced after all a waster. It is easy then to lay the blame—and rightly—on the design of the tool or the manner of quenching it. The question, however, is how to prevent the breakage, and no answer, in the form of general rules, can be given save such as have already been discussed on previous pages. The veriest novice, as we have said, can detect flagrant overheating in tools which he himself has not hardened. And it is safe to affirm that, with few exceptions, all forms of cracking are greatly encouraged by overheating because it increases the permanent expansion, *i.e.* the induced stress, and at the same time decreases the strength of the material. Especially does it increase the ease with which the apparently insignificant beginning of a crack—such as deep tool marks—can develop and extend.

It is, however, by no means safe to assume that a coarse fracture is necessarily due to incorrect hardening heats; it may be simply an indication that during some preceding

operation the material has been burned or soaked at too high a temperature. Experience in distinguishing these differences, which can only be described by such lame phrases as "dry" or "staring," is best obtained by careful observation of comparative specimens cut from the same bar of steel. In this manner one may detect differences between material which has been overheated and "restored" and material which has not been overheated that would otherwise escape notice. The piece of steel represented in Fig. 47 was taper heated and quenched; it was then retreated and requenched, but not by any means restored to the same condition as before overheating.

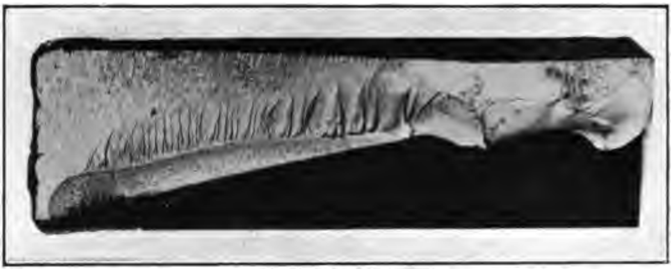


FIG. 47.—Taper overheated and "restored": effects of overheating still visible.

The effects of overheating are still visible on the left-hand side.

The sharp corners of such tools as chisels, plane irons, roll turners' knives, etc., are at times overheated on the corners only and not at all in the thicker hardened parts. This is an indication that the tool has been heated quickly in a furnace much hotter than the correct hardening temperature by an inexperienced or careless person. In its effects this treatment may be worse than out and out overheating, as the lack of uniformity nearly always causes the corners to spring off.

SHEARED ENDS.

Material which has been worked cold, whether hardened or not, is very apt to develop cracks. High tensile rope wire, for example, in the drawn state splits longitudinally with remarkable ease once a small notch has been made on the surface. Small sections of hard steel are frequently

sheared into definite lengths for making small punches, drills, etc., but unless the portion of material affected by the shearing strains is machined away, the hardening operation will surely develop an unpleasant percentage of wasters. It also happens occasionally that a shape free from sharp angles and corners has been set out for machining by centre punch marks. These represent points from which a crack in intensively hardened steel can readily originate, and if they have been almost entirely machined out, as is usually the case, it is very difficult, unless fully acquainted with the circumstances, to account at all for the cracks.

X

HARDENING PLANT

THE following conclusions will not be seriously contested by persons acquainted with the facilities generally provided for hardening purposes :—

(1) The equipment of a hardening shop rarely gets the attention it deserves.

(2) It certainly would be difficult in a shop doing general work to provide spick and span appliances for every job that might come along.

(3) Successful artisans in this trade have developed the habit of improvising makeshifts.

(4) Helped by native ingenuity a really first-rate man turns out some astounding pieces of work with a mere handful of regular tools.

(5) So far as the experiment has been tried, the "really first-rate" man does not seem to be spoiled at all when he gets a few specially designed furnaces and loose tools.

For reasons we are already acquainted with, it seems desirable that the heat of a furnace should not be greater than the temperature to which the tool needs to be raised for hardening. It requires otherwise an unusual degree of skill to avoid overheating the corners and thinner parts ; and the outer portion must unavoidably be hotter than the interior. Also judgment and ceaseless attention are required in order to determine when the hardening temperature has penetrated throughout.

OPEN FIRES.

The ordinary smith's fire is about the worst conceivable form of furnace for hardening purposes ; but it is very handy and inexpensive for occasional jobs, and on this account, though it possessed every objectionable feature possible, it is likely to remain in use and had better be

made the most of. No form of pyrometer can be used in this furnace save such indicators as are mentioned on page 115. To completely smear the point of a chisel with a fusible paste is the easiest way of observing the irregular manner in which tools are brought up to and beyond the hardening temperature. To obtain anything like uniform heating it is necessary to turn the tool about continually and withdraw it frequently from the fire so that the heat may become approximately uniform owing to the more rapid cooling in the air of the corners which have heated more rapidly in the fire. The open fire can be arranged for temporary purposes and manipulated in various ways to meet to some extent the more exact conditions required for delicate work. The simplest of these ways is to pile damp smithy coal over the hearth and blow the fire till a hollow space has been burned out. From this improvised muffle of glowing fuel very tricky hardening jobs can be done with some precision. Small pieces of coke must be occasionally thrown into the fire, and if it needs brightening up also a few puffs of wind. The arch is kept intact by adding fresh layers of damp coal; it gets gradually larger of course and is then used for larger tools which have been reserved till the last.

If a supply of strongly caking coal is not available, or if only an odd job requires doing, it is easier to build the fire about a piece of wrought-iron or cast-iron piping and harden from the inside of this. The metal is a good conductor, and on that account the heat is more uniformly distributed inside it than in an earthenware pipe or muffle; and though the metal piping rapidly burns through it can be replaced for next to nothing from the scrap heap. For handling small taps or drills a blind flange from the gas-fitter, a used shrapnel, or even an old iron saucepan can be packed into the fire and filled with lead or salt in order to secure the advantage of heating a large number of tools simultaneously in a uniform manner.

Where a hearth is used only for the smithing and hardening of tools an arch may be built permanently over it, as suggested by Fig. 48. Once the arch has become thoroughly hot it radiates back a good deal of heat and

helps to keep the temperature uniform. The coke fuel falls through a slit in the top towards the back end, and the whole can be closed up so that the only means of exit for the burnt gases is either of the two front holes, which may be closed if thought desirable with loose bricks. This decreases the tendency to scale. This furnace is also a convenient one of its kind for hardening high-speed steel as well as ordinary carbon steels.

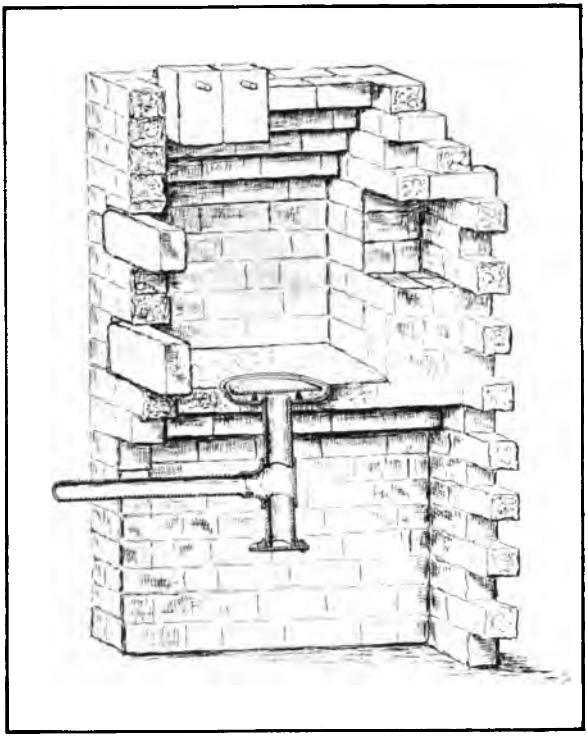


FIG. 48.—Smith's hearth modified for hardening purposes.

OPEN HEARTHS.

A great variety of furnaces are in use, fired with solid, liquid, or gaseous fuel, to meet particular requirements. A selection of furnace-makers' catalogues[1] being easily

[1] Hardening furnaces are made, amongst others, by Fletcher, Russel & Co., Warrington; Richmond Gas Furnace Co., Warrington; Brayshaw, Manchester; Allday & Onions, Birmingham.

obtainable, there is no need to reproduce structural details here. Solid fuel is gradually falling out of use, and can only be recommended either on the ground of economy, or convenience in localities where neither gas nor oil are plentiful and cheap. A reverberatory hearth burning coke mixed with a small quantity of coal is sketched in Fig. 36. The general arrangement is typical of furnaces burning solid fuel which are at present in use for heating different kinds of tools. Relative dimensions vary, of course, and special care must be taken to provide efficient dampers; it is also a convenience to control the draught by means of a door, opening upwards, on the ashpit.

OIL AND GAS.

Improved burners have almost entirely done away with the uncertainty formerly associated with oil furnaces, and very crude forms of oil can now be burned without interruption, which brings down the expense sometimes below the cost of coal gas. In point of convenience, however, coal gas (or producer gas) is superior to any other kind of fuel. It can be used with atmospheric burners in any of the usual forms of hardening furnaces to attain temperatures up to 1000° C. For general purposes a tray, which may be of cast iron or boiler-plate steel, is better than a muffle, as the burnt gases surrounding the work in the former case are less harmful on the whole than the oxidizing influences of the undiluted air within the muffle.

Compressed air considerably extends the usefulness of gaseous fuels, and it is sometimes advisable to use it even for lower temperatures in order to drive the heat in any desired direction independent of flues. If the supply is taken from a main or some source not especially provided for the purpose, then some means, which can be readily rigged up and discarded, of varying and limiting the pressure is useful. Fig. 49 is a simple piece of laboratory apparatus and does very well.

The air comes in from the main at A and out to the furnace at B. The pressure is regulated at will by the depth to which the long tube dips below the surface of the mercury. If the required pressure is exceeded, the mercury is pushed back and the excess of air escapes through E. Some tests made by compressing the gas instead of the

air appear to have been very successful. On purely theoretical grounds there should be an advantage in having to control the pressure of gas only, as the pressure of the air at normal temperatures is practically constant.

The chief value of gas or oil-fired furnaces is not that they are cleanly in use or can be quickly brought to any desired temperature, agreeable as these features are. It is rather the possibility of keeping the required temperature

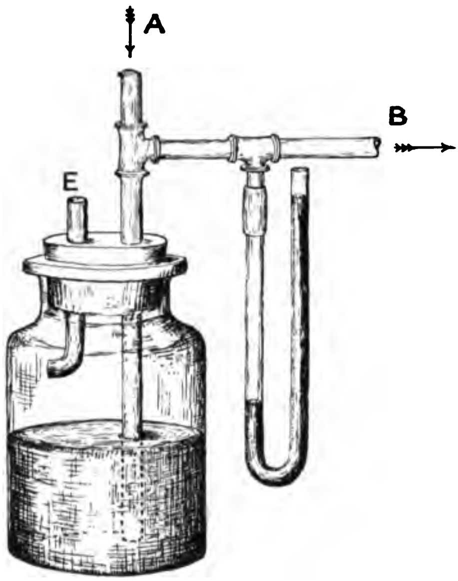


FIG. 49.—Simple arrangement for regulating air pressure.

uniformly the same for any desired length of time. And so, presuming the gas supply is constant, the furnace may be raised to a suitable temperature and the tools allowed to remain in it until they also reach that temperature. This lightens the responsibility, makes overheating impossible, and with articles of the same kind greatly facilitates the work. It is necessary, however, in the first instance, to look not only to the gas cock but also to the dampers in order to avoid irregularity and scaling.

LEAD BATHS.

For many years lead has been utilized in the hardening of files, drills, and edge tools generally; chiefly because it affords, with reasonable care, a uniform heating medium.

The specific gravity of lead is very high—higher, in fact, than the specific gravity of steel—and for this reason the article to be heated must be forced into and held down in the bath. The lead has also a tendency to stick in cavities and between teeth, and is easily oxidized, and for other reasons could not be generally used with furnaces of large dimensions. Lead, it is said, can also dissolve its own oxide and sulphide, and through the agency of these substances cause soft spots. One cannot, however, be dogmatic on this point, as such uncertain statements are frequently stretched to explain remote and quite unrelated causes. It must not be presumed that because the heating medium is liquid it is therefore uniform. It is necessary to stir the liquid from time to time, especially if it is heated merely from the bottom over a coke fire or on one side only by being set in a flue.

SALT BATHS.

By merely substituting salt for lead in the old form of pot, we handicap the salt bath to a serious extent. All salt mixtures suitable for steel-hardening purposes melt at a temperature considerably beyond the melting point of lead, and, as salt mixtures are much worse conductors of heat, it is difficult to avoid the incrustation of frozen salts about the top of the pots. From this cause, no doubt, arose the practice of adding substances such as nitre, soda ash, and caustic soda to the salt mixture in order to reduce its melting point, and for this reason many undesirable features have become associated with the salt bath, which can easily be avoided in a properly designed furnace.

FIG. 50.—Brayshaw's salt-bath furnace.

Considerable impetus has been given to the use of salt baths in this country by Mr. Brayshaw, of Manchester; a view of his furnace is given in Fig. 50. There is probably

no furnace extant better suited for exact work of an ideal kind, though opinion is somewhat divided over its merits as a workshop tool; the writer, however, has had no personal experience with it, and can therefore make no comment.

A simpler form of furnace is illustrated in Fig. 51. The furnace body consists of a wrought-iron cylinder with brick lining. There is an intermediate air space to reduce

FIG. 51.—Very simple form of salt-bath furnace.

radiation, and for the same reason a sheet of asbestos is sometimes laid on to the outer surface of the wrought iron. A single burner of the annular type rests on the bottom of the furnace body, and the pot containing the salt mixture is supported by lugs, or a perforated rim, which rests on the brick lining. The flame and hot gases, in passing between the outer surface of the pot and the inner surface of the brick lining, give up much of their heat to numerous studs projecting from all parts of the surface of the pot, and are

eventually diverted on to the surface of the molten salt by means of the curved cover. In this way the pot is evenly heated to the extreme upper edge, and an accumulation of frozen salt becomes impossible. At the same time the products of combustion impinging on the surface of the salt, or lead as the case may be, minimizes the amount of atmospheric surface oxidization.

PROPERTIES OF MOLTEN SALT.

On immersing a tool in the molten salt-bath, the temperature of the salt in its immediate neighbourhood is reduced below the melting point, but causes a layer of salt to freeze around the tool. This salt layer is a comparatively poor conductor of heat, and remains almost intact until the tool has gradually absorbed sufficient heat to raise it to the melting point of the salt. In no case can this occur below low redness, and after that a more or less rapid heating is unavoidable. On withdrawing the heated tool, the molten salt adheres and completely envelops it. On this account the temperature of the tool falls more slowly and regularly. The salt sheath, however, does not interfere with the quenching, but dissolves as soon as it comes in contact with the water, and leaves a clean metallic surface barely oxidized or even tarnished.

ADVANTAGES OF SALT BATH.

A further advantage, which is not so well known and has been very little utilized, is the ease with which the melting point of the salt-bath mixtures may be varied. Assuming that we have to deal with a steel which must be heated to at least 750° C. in order to harden it at all, we may, by way of example, choose a salt mixture for the bath which melts at 760° C. The minimum hardening temperature must obviously be maintained in order to keep the bath molten, and the steel object being handled must also reach nearly the same minimum temperature before the salt, which on immersion immediately congeals around it, can melt off. A temperature of 20° C. or even 30° C. beyond this minimum, unless unduly prolonged, can do the tool no harm, and it is an easy matter for an inexperienced workman, without the aid of any form of pyrometer, to keep within this margin. On withdrawing the tool from the furnace, after the congealed salt has melted clean away, the liquid salt drips off, but very shortly a coating of it

crystallizes on the surface, and indicates that the quenching should be proceeded with.

This mode of hardening is certainly a great improvement in point of accuracy on the usual shop practice, and is quite independent of the workman, the state of the weather, or other possible contingencies. But it is rather slow, and does not reach the best attainable hardening conditions required for faultless work on complicated shapes of varying section. The thinner sections and corners of such tools will always heat more rapidly in any furnace—though the difference is less marked in the salt bath than in other forms—than the more massive parts, and as uniform heating is essential to success, it is necessary to insist on the temperature of the furnace itself being correctly regulated, so that objects being hardened may be left exposed to the heat as long as is necessary for all parts to become evenly heated throughout, without any of the parts becoming overheated. That is to say if the temperature of the furnace is uniform and suitable, the temperature of the object may, generally speaking, be left to take care of itself.

IDEAL CONDITIONS.

From these considerations and the indications of the thermal curve already mentioned (Fig. 24), we may arrive at what are believed to be the ideal conditions of steel hardening as far as they can be stated in general terms. That is to say, the objects should be heated some twenty or thirty degrees beyond the thermal change-point on the heating curve, and be allowed before quenching to fall to a uniform temperature some ten degrees above the cooling change-point.

These stipulations cannot very well be carried out with one salt-bath furnace, because the intermediate cooling in the atmosphere through a large range of temperature, say from 780° to 710° C., is not quite uniform, in spite of the protective salt coating. The operation is more precisely carried out as follows, but still, be it noted, without necessarily making direct use of any form of pyrometer:—

In the first place, the object is heated some 30° C. beyond its minimum hardening temperature in the salt bath as already described or in any other form of furnace. It is

then transferred to a second bath, whose melting point is say 710° C., and whose temperature is easily maintained at quite negligible cost, by the heated objects constantly being added, several degrees beyond this. In this second bath the object cools uniformly to the prevailing temperature, and on withdrawal is enveloped in a coating of fluid salt, which, after a moment's delay, crystallizes over the entire surface, and indicates that the quenching should be made.

Thus are the stipulations of the modern theory and practice of hardening satisfied. The seeming complication has no real existence. The method is admirably adapted to the quick despatch of regular work, whether of a repeat or varied kind, and the refinements can be easily dropped or taken up according to circumstances. Moreover, a couple of furnaces having circular baths eight inches diameter by ten inches deep can be accommodated in twenty square feet of floor space, and be installed for from twenty-five to thirty pounds.

SOFT RINGS.

It is occasionally necessary to harden one end, side, or surface of an article without hardening the rest, or to preserve the centre, or a strip round the middle of an object, in the unhardened state. Even where special appliances are available the risk of dangerous tension between the hardened and the unhardened parts is often very great. With a couple of furnaces some difficult operations of this kind are fairly easy. The object is heated in the first bath as usual, and on withdrawing is cooled on the parts which are to remain soft by the application of pads of wet asbestos, etc., until the temperature of these parts has fallen below 680° C. say, to a scarcely visible redness. In the mean time the remaining uncooled parts will not have fallen by any means so low as 700° C., and after immersing in the second bath the temperature becomes equalized. But on withdrawing from the second bath and quenching, although the temperature is uniform throughout, only those parts of the object which were not cooled below 680° C. will become hard, and between the hardened and unhardened portions the greatest attainable graduation of tension will exist.

SPIKE INDICATORS.

We have already referred to the ease with which the

melting point of the salt bath can be varied at will within certain limits and used to control its temperature without the use, if need be, of a pyrometer. It should also be said that the melting points of some mixtures remain practically constant over long periods, in spite of the small amounts of oxide of iron which accumulate and float about in the bath. This feature enables a very inexpensive but fairly accurate form of temperature indicator to be used which is called the "spike."

The "spike" is nothing more than a round piece of wrought iron which tapers from one end to the other. On immersing such an object into a bath, the quantity of salt

FIG. 52.—Examples of "spike" before and after use.

which congeals around it will obviously depend on the number of degrees the temperature of the bath is over and above its melting point. It is equally obvious that the rate at which the congealed salt dissolves off again will depend on the same circumstance. If, therefore, the "spike," when immersed, is always at a constant temperature, say 100° C., and allowed always to remain in the bath for say one minute, then the weight of the salt still adhering, or otherwise the length of the spike from which the salt has clearly

melted, will be a measure of the temperature. See Fig. 52.

The "spike" is calibrated once for all by comparison with a standard thermo-couple, and may then be duplicated to any desired extent. Previous to immersion it is kept at a constant temperature of 100° C. in a piece of apparatus made from an ordinary lever-lid tin as shown in Fig. 53.

DISADVANTAGES OF SALT BATHS.

The melting points of salt mixtures suitable for use in hardening ordinary carbon steels vary between about 650° and 800° C., and for tempering the same from about 200° to 350° C. At temperatures much above their melting points the former vaporize to a slight extent and cause iron objects in their neighbourhood to rust quickly. Small particles of iron in the form of magnetic oxide accumulate in the bath and may adhere to very fine-toothed articles such as files, and cause the tips of the teeth here and there to remain soft after quenching. If the files are dipped into a solution of ferrocyanide and allowed to dry before putting into the bath, this does not occur. The remedy, however, is not quite satisfactory, as each coating of ferrocyanide decomposes and adds more iron oxide to the bath. Potassium cyanide would be free from this objection, but it is so poisonous a substance that its regular use cannot be recommended. Experiments made with other substances of a harmless kind have not been at the same time successful and commendable, and one is obliged reluctantly to conclude that, so far as files are concerned, the lead bath is preferable.

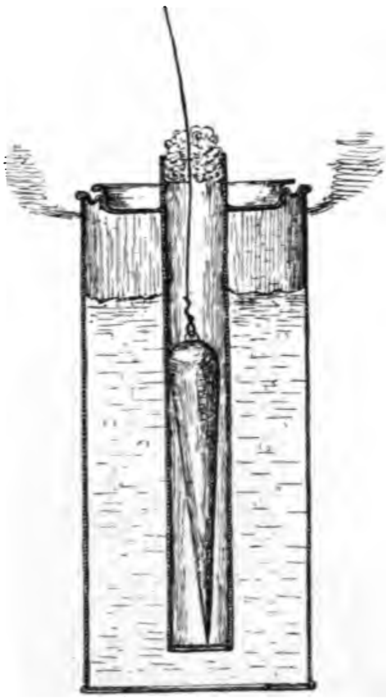


FIG. 53.—Arrangement for keeping the "spike" at 100° C.

QUENCHING TANK.

A plain rectangular cast-iron trough, an old tub, or even a bucket may in some circumstances be everything that is required for holding the hardening fluid. For varied work, however, a tank which can be readily adapted to special purposes is a great convenience. A good supply of water should be led into it from the bottom and branch into at least two arms, as in Fig. 54.

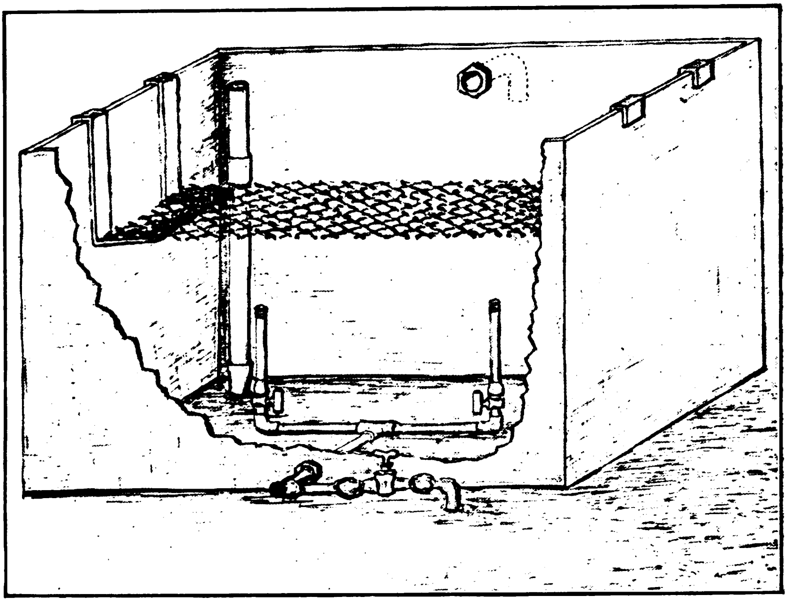


FIG. 54.—Universal hardening tank.

These branches are screwed at the ends so that any desired fittings, such as those already mentioned in Chapter VIII, may be easily and firmly attached. The waste pipe at the top of the tank may empty around an adjacent oil tank for cooling purposes, or directly into the drain. The upright pipe in the left-hand corner fits into a taper hole in the bottom of the tank which serves to empty the tank entirely. The upper part of this pipe should be wider than the lower half, and screw over it to any extent in order that the water in the tank may be arranged and maintained at any desired level. The perforated grid which hangs from the sides is intended, in conjunction with the adjustable

overflow pipe just mentioned, to facilitate the quenching of objects which are hardened over a definite part of their length only. The fittings suggested by Figs. 38 and 39, and others already referred to, indicate to some extent to what varied uses a universal tank can be put; but the main advantage lies in its adaptability to any unusual job which may be presented.

Although we have intimated that the waste water may be used for cooling an oil tank, it is really a very inefficient way of cooling oil to pass water about the containing vessel, because the oil itself is a poor conductor of heat. A readier way of cooling a small quantity of oil is to blow air through it; or, if the quantity is large, to pump it through a nest of small water-cooled pipes.

LOOSE TOOLS.

The equipment of a hardening shop includes also an assortment of loose tools which need not be separately described; tongs of varied lengths and strengths with curved and straight jaws, so that an object may be readily and suitably handled; rods of iron for making into hooks; and sheet-iron and asbestos for protecting the parts which require heating very slowly or not up to the hardening temperature; iron piping, casehardening boxes, or any receptacle which can be closed, and a supply of iron and steel filings so that an article may be packed for close annealing; and scores of other things which can frequently be picked up from the scrap heap and cost nothing, but are worth a great deal when a chance job has to be done quickly and well.

A pair of tongs with long jaws is very convenient for holding a quantity of drills, bits, etc., which require to be heated in molten lead at one time. If the articles are of uneven thickness and one jaw of the tongs be made hollow and one flat, a piece of soft wood may be put in the hollow jaw so as to grip all the drills.

XI

PYROMETERS

GENERAL CONSIDERATIONS.

THE metallurgical millennium promised to all who would install pyrometers in their furnaces is still a long way ahead. Respecting the importance of pyrometric control of furnaces used for annealing and hardening there can be no question; but obviously the difficulties of quenching, etc., remain as great as ever. Having obtained pyrometers to register and control furnace temperatures, it has, in many instances, been found necessary to obtain some one to look after the pyrometers. The experienced workman who judged by the eye, now and again, either for particular or diverse reasons, made mistakes, but also the pyrometer may do so; and whereas the workman generally righted himself in time to within his usual limits of error, the instrument generally goes from bad to worse.

It is not necessary to enumerate the diverse reasons for which a pyrometer may give incorrect readings. It is, however, important to note that the defect may appear suddenly or increase gradually, and in either case without being suspected; particularly if the instrument is (wrongly) regarded as a substitute for the human eye and judgment, and these latter, being no longer trusted and responsible, are no longer trained and consciously used to determine temperatures. In any case it is necessary that the instruments should be regularly proved and standardized.

LARGE FURNACES.

An oft-quoted rule, which is supported alike by considerations of economy and experience, is this: "Use the lowest temperature which enables the desired result to be obtained." And an effort often made after installing a pyrometer is to arrange the temperature as near the margin as possible. The "irreducible minimum" in temperature is a two-edged sword for the average operator who decides

to surrender his judgment to the indications of a pyrometric indicator; the step usually leads to considerable trouble, but also to much instruction. The danger lies, to some extent, in the fact that industrial furnaces have never the same uniform temperature throughout their length and breadth, or from bed to roof. Something less than the temperature registered by the pyrometer, which is that of its immediate neighbourhood only, is attained in other parts of the furnace, and consequently some of the objects being heated, or parts of them, do not respond to the treatment. The pyrometer, of course, is not responsible for the disappointment, as it has never been claimed that the instrument will overcome faults in furnace design, although it is much to its credit to have shown so clearly how badly reheating furnaces are frequently constructed.

The idea of an "irreducible minimum" in temperature must be compromised with, and it is advisable, if the instrument has not been firmly fixed, to take readings of different parts of the furnace and plot out a temperature chart. If this is done for different modes of firing or charging the furnace, the trouble involved is well repaid by the information gained. The variations disclosed by such a survey are usually surprising, and as uniformity of temperature in any object being treated is generally of much greater importance than very exact readings on a temperature indicator, it will be conceded that there is scope between the neighbourhood of the pyrometer tube and the four walls of the furnace for human judgment and the best rule-of-thumb practice, as well as other qualities which cannot be hitched on to a wire or regulated by clockwork.

RULE OF THUMB AND SCIENCE.

The influence of pyrometers on the design of industrial furnaces has already been considerable. But engineers are rarely expert furnacemen, and the important finishing touches and minor alterations which make a furnace work reliably and uniformly are frequently made by ingenious workmen in ways difficult to describe. It is nearly always a mistake to instal a pyrometer in opposition to a man; to fasten it into the furnace and enforce its indications willy-nilly is the least profitable use to make of it. A very

moderate workman is a long way ahead of the best instrument used in that manner. The freer the instrument is to be used now in one part of the furnace and then in another, as the judgment of the workman demands, the more interest he takes in it, the less he feels his skill to be superseded by it, and the more perfectly the desired object of heat treatment can be attained. The control which an intelligent man with such assistance obtains and can exercise over his furnace is quite remarkable and gratifying.

One hears too frequently from people who, through neglect, are disappointed in the original and obvious use of a costly temperature-recording instrument, that it nevertheless is worth the money as a check and tell-tale to announce, without fear of intimidation, when the firer has been asleep or for other reasons neglected his duty. Such instruments are not worth consideration as pyrometers, and it may be suggested that people do not fall asleep over work they are interested in. A firer who was fit for his duties, given a suitable instrument, might keep himself awake and go very far towards removing the vexatious variations of temperature which father innumerable evils and against which a fixed indicator is of little value. This way promises better than any other way to improve the design and bring the temperature of large furnaces under ready control.

OPTICAL PYROMETERS.

The man who tells temperature "by the eye" uses a kind of optical pyrometer, *i.e.* the sensation of a colour which changes as the temperature rises. This primitive kind of instrument is wonderfully sensitive, but not thoroughly reliable. It is subject to physiological derangement; it also does not enable the observer to state temperatures in precise terms, and therefore does not provide accurate information for general use. The sensation of colour is comparative, and depends entirely, so far as brightness of colour is concon-concerned, on the condition of the surrounding objects. Changes in the sky, in the artificial lighting of the shop, or the flame emitted by the furnace itself even, need to be taken into account. In order to help out the insufficiency of the eye, red glasses of different tints are occasionally used, which, on being illuminated from the back by some

unvarying source of light, enabled them to be looked to as standards. Varied suggestions akin to the above have been proposed over and over again, but appear to be only rarely used.

WANNER.

A really serviceable instrument based on a comparison of colours, one of which can be varied at will according to a numbered scale until it corresponds in brightness with the heated area under observation, is known as the Wanner pyrometer, and is made by The Paul Schmidt and Desgraz Co., Ltd., of London. See Fig. 55.

FIG. 55.—The Wanner pyrometer.[1]

When first introduced it could not be used for temperatures below 900° C., but it worked very well at higher temperatures. It is generally considered to be better than any other instrument for taking the temperature of molten metals or metal-melting furnaces, though a really satisfactory apparatus for this purpose, so far as steel and some other

[1] It seems needless to describe the construction of any of these instruments, as such information is always available in trade circulars and is constantly appearing in technical journals.

high melting-point metals are concerned, has not yet been devised. The Wanner outfit is now made for temperatures down to 600° C.

FÉRY. Two forms of the Féry pyrometer are in use. The older form consists of a tube containing a delicate thermo-couple exactly in the focus of a silvered concave mirror which reflects the heat rays of the furnace on to it. The temperature of the couple is then indicated on a sensitive millivolt-metre. The newer form does not vary much in appearance from the older, but the thermo-couple at the

FIG. 56.—Sighting the Féry radiation pyrometer.

focus of the mirror is replaced by a coil of two dissimilar metals which unwinds more or less according to its temperature. The coil is very small and fastened at one end; the other end is attached to a small aluminium pointer which moves over a graduated dial. These instruments require to be accurately focused and carefully handled.[1]

[1] A fixed focus optical pyrometer is made by the Foster Instrument Co., Letchworth, Herts.

They are claimed to be universally applicable, but appear to be better adapted for giving indications and making records of temperatures of furnaces which are operated without interference for long periods—such as annealing furnaces, casehardening ovens, and automatic hardening machines. The first form, at least, does not give anything like an accurate indication of the temperature of molten steel as it runs from the furnace.

RESISTANCE PYROMETERS.

The essential part of resistance pyrometers is a fine platinum wire, wound on a mica frame, whose resistance to the passage of a small current increases at a rate nearly proportional to the temperature. As electrical resistances can be very easily measured, this form of pyrometer is more sensitive than any other. It is especially well suited for use in positions where it can remain for long periods undisturbed, such as in hot-blast main (see Fig. 57), furnace flues, salt-bath furnaces, etc. It is also especially valuable where changes occurring over a short range of temperature need to be carefully observed, as the instrument can be adjusted to almost any degree of delicacy. It is, however, expensive, it is limited to temperatures well below 1200° C., and the cost of replacing the porcelain sheaths which protect the couple may be a serious item unless it is cautiously handled. It is also not easily repaired except by a skilled man, which involves the unavoidable delay and annoyance of returning it to the maker.

FIG. 57.—Mode of using resistance pyrometer.

THERMO-COUPLES.

The "couple" temperature reading outfit is more widely

used than any other, and therefore requires fuller consideration. It consists in principle of two wires of dissimilar metals fused together and in that form known as a couple. When the junction is heated an electric current is generated whose electromotive-force varies with the temperature and is measured by means of a millivolt-meter. For tempering baths or work which does not involve temperatures beyond 650° C., a couple consisting of one wire of silver, or copper, and the other of constantan[1] can be used; such couples are very cheap, and can be easily replaced. For moderate temperatures, say up to 900° C., couples made from the more refractory baser metals may be used; they too are cheap and give widely spaced readings on strongly built indicating instruments. But for all ranges, including high-temperature work, only two kinds of couples are in general use. In both, one wire consists of platinum; the second wire in one case is made from an alloy of platinum and iridium, and in the other from an alloy of platinum and rhodium. The two kinds of couples are then spoken of as platinum-iridium and platinum-rhodium couples. The former generates the greater electromotive-force for any given difference in temperature, and therefore the scale on the indicating instrument is a more open one; it is also somewhat cheaper. But these advantages are more than counterbalanced by the fact that iridium couples are more apt to become brittle and are considerably damaged at temperatures of 1000° C. and over. To avoid being misled by these changes it is necessary to restandardize the couples from time to time. The changes in E.M.F., according to Stupakoff[2] and others, occur at about 1800° F. (983° C.), and are due to partial volatilization of the iridium which occurs at this temperature. Platinum-rhodium couples can be safely used at much higher temperatures, preserve a constant E.M.F. for longer periods, and are less brittle after extensive use. No kind of couple should be needlessly exposed to high temperatures.

PROTECTING TUBES. Either kind of couple can be easily damaged by careless use. The unprotected wire should not be exposed to the

[1] An alloy of copper and nickel of high E.M.F.

[2] *Iron and Coal Trades Review*, November 26, 1909, p. 853.

action of reducing gases; a stream of unburnt coal gas impinging on the naked wires will make them exceedingly brittle in a few hours. Contact with oxides of iron and some silicates is also very objectionable, and they must, of course, be rigorously protected, like all platinum goods, from contact with metals or metallic fumes with which they readily alloy. The two wires are insulated by passing them through parallel holes in short lengths of clay or porcelain rods. The bottom rod is countersunk on the end so as to protect the actual junction, and the whole is mounted in a protecting outer tube which in its simplest form can be put together from ordinary gasfitter's stock (Fig. 58).

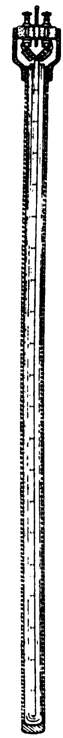


FIG. 58.—Protecting tube made from gas-fitter's stock.

As hot iron is pervious to gases and to molten lead or the fumes arising from it, an inner protecting tube is desirable and sometimes indispensable. If this inner tube is made of porcelain it must be cautiously heated and cooled, otherwise the cost of replacing it will soon amount to more than the value of the couple itself. Inner tubes made from fused silica will bear suddenly heating or cooling better than porcelain ones, but they deteriorate rapidly at temperatures much over 1000° C. In the atmosphere of most industrial furnaces a couple without the inner protecting tube lasts very well and stands an amount of unavoidable rough usage which would break fragile porcelain or silica tubes many times. There is, of course, a greater risk of spoiling the couple itself, and perhaps a need for more frequent standardization. Taking, however, one consideration with another, it is cheaper to use internal tubes of fused silica than to replace couple wires more frequently as would be otherwise necessary. There may be some danger of the fused silica breaking under the weight of the iron tube, which bends at high temperatures. This can be avoided by using a wider iron tube cut away at the lower

end so that the silica tube projects through it one or two or more feet according to circumstances.

RECORDERS.

With many forms of apparatus now available the temperature may be read off as required, and also at the same time be automatically and continuously recorded. Those recorders depending on the photographic development of an image traced by a spot of light reflected from a mirror galvanometer are less convenient than those whose records are visible any time after they are made. These latter are traced on a drum or on a sheet of paper moving horizontally by an arrangement which depresses the needle of a millivolt-meter each minute or oftener. They can also be used for recording simultaneously the temperature of several furnaces with the aid of a self-acting switch which connects the terminals of each couple in turn with the recorder. Of the various forms of instruments now being sold, Fig. 59 represents only one of many reliable

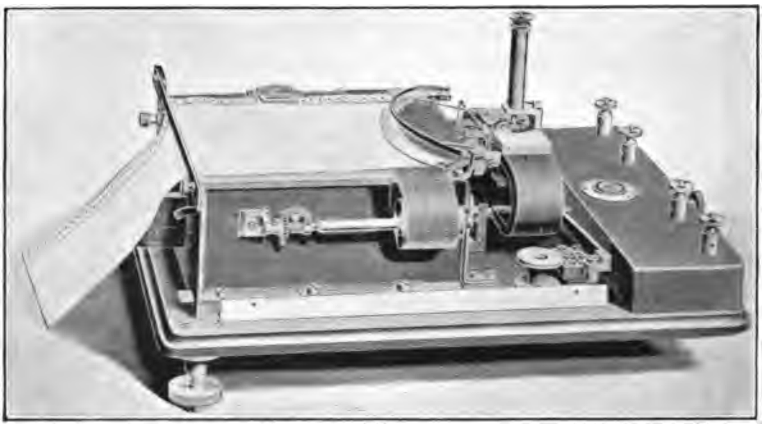


FIG. 59.—Siemens recorder with cover removed.

types. Thermal curves which clearly show the critical change points on heating and cooling can be traced with next to no trouble, and without any regard to the shape of the specimen, on a good recorder.

COLD JUNCTIONS.

The end of the couple inserted in the furnace is spoken of as the hot junction (H.J.), and the other end connected to the brass terminals in the head as the cold junction (C.J.). The current registered on the indicator depends on

the difference in temperature between these two ends. But the reading on the indicator would not be the same, *e.g.*, under the following circumstances:—

H.J. 700° C. – C.J. 0° C. difference 700° C.
H.J. 750° C. – C.J. 50° C. difference 700° C.

although the difference in temperature between the two ends is the same in either case. The irregularity is due to the fact that the E.M.F. generated is not strictly proportional to the temperature, and cannot, therefore, be represented by a straight line. In order to avoid any error creeping in through this cause, it is advisable to standardize the instrument in the first instance under practical conditions, that is to say, with a C.J. of 25° C. If in actual use the C.J. deviates appreciably from 25° C., then the difference after multiplying by 0·75 should be added or subtracted accordingly. The result will be correct to within two or three degrees over a range of variation in cold junction temperatures between 20 and 90° C.

REPAIRING THERMO-COUPLES.

As all forms of thermo-couples are subject to varying degrees of deterioration or may get accidentally broken, it is a great safeguard and convenience to be able to do simple repairs and calibrations on the spot. Defects in recorders and indicators rarely arise, and can be dealt with only by an experienced instrument-maker.

The re-fusion of a broken couple is frequently necessary, but can be carried out in a few minutes. A stream of compressed oxygen is allowed to pass through a small blowpipe—such as is used for blowpipe analysis by prospectors—into the flame of an ordinary spirit lamp The deflected portion of the flame is very hot, and suffices to melt the two ends of the broken couple which are brought together within its range. Made in this way, the fused junction after a little practice consists of a small sphere of metal the size of a pin's head with the wires running smoothly away from opposite sides of it. The two wires may also be twisted together over a length of two or three millimetres and the extreme end fused as before; this method requires less skill, but does not make so neat a finish about the junction.

CALIBRATION.

The laboratory method of calibrating is to insert the couple into molten substances which have a definite freezing point, and during cooling to observe the position on the scale at which the temperature remains constant owing to the evolution of the latent heat of fusion. This is also the most suitable method for industrial purposes, presuming that correct substances, having definite freezing points, are chosen. The substances chosen should have the following properties:

(1) The freezing point should be sharp and continuous for at least as long as is necessary to comfortably make an observation.

(2) It should not be subject to oxidization, and its freezing point should not be altered if it should chance to become oxidized.

(3) Its indication should be the same, however often the observation may be made.

(4) It should not attack the iron casing of the couple, nor should it be injuriously affected by contact with the iron casing at high temperatures.

In short, what one requires is a substance that can be melted in an iron or a graphite pot in a smith's hearth without any of those special precautions which, though easily complied with in the laboratory, it is almost impossible to observe in the factory.

Tin, lead, and zinc can be used, and are easily obtainable in a sufficiently pure state, but they oxidize very readily, and, moreover, their freezing points—232° C., 327° C., and 419° C. respectively—are too low for general use. The freezing points of antimony (632° C.) and of aluminum (657° C.) come nearer working temperatures, but these metals are not easily obtained of a sufficient degree of purity, and they also readily oxidize and are otherwise easily contaminated. Silver, which freezes at 962° C., is excellently suited for the purpose, but it is expensive. Copper may be used, but its freezing point, 1084° C., is subject to a variation in temperature of 10° C. by exposure in the molten state to the atmosphere.

While, therefore, metallic substances can be satisfactorily used under suitable conditions, they are by no means as convenient as could be desired, nor do the freezing points of those which might be used fall within the temperature

range mostly used in the heat treatment of steel and iron. On the other hand, however, some salts of the metals meet almost every requirement, and from among the great number of mixtures which can be prepared a suitable substance may be selected for making a calibration in any desired range of temperature.

Take for example ordinary table salt; not any of the fancy salts or the non-caking varieties, which contain something else besides salt, but the common loaf brand. Its freezing point lies always between 795° and 800° C., and the same material can be used over and over again with perfect satisfaction. The manner of using it is as follows: Fill an iron or a plumbago crucible which will hold about a pint with the crushed salt and set it on a smith's hearth, or heat it by any other available means until the salt becomes quite molten. Then place the warmed end of the couple into the molten salt and close to the other end (the cold junction) tie a thermometer, or insert one through the head as shown in Fig. 58. When the hot junction has had time to attain the temperature of the molten salt, remove the crucible from the fire, or turn off the gas, and pack it amongst dry warm coke. Now carefully observe the indicator, which begins gradually to fall. As soon, however, as the salt begins to freeze, the indicator remains stationary or it may even rise slightly, and it does not again begin to fall until the salt is quite set. Observe also the temperature of the cold junction as indicated by the thermometer and calculate as follows:—

Instrument, originally calibrated at say ...	25° C.
Pointer came to rest against mark	790° C.
Cold junction temperature	30° C.

Therefore, 790° C. on the indicator corresponds to $800° \text{ C.} - (30 - 25) \times 0{\cdot}75 = 796° \text{ C.}$, that is, the instrument is indicating four degrees low.

The salt may be remelted in a few minutes in order to repeat the observation; and finally the crucible, when cold, may be wrapped in paper and kept available at a minute's notice to check any instrument which may be in use.

It may be, and usually is, desirable to have several

substances whose freezing points lie along the range of temperature over which the pyrometer is being used. Such substances, in the form of salt mixtures having guaranteed freezing points, are manufactured by the Amalgams Company, Ltd., of Sheffield.

In using either salt mixtures or any other substances for calibration purposes it is absolutely imperative that all traces of one substance be removed from the couple before it is immersed in another substance. If salts are used it is sometimes much easier to slip off the iron tube and immerse the naked couple in the molten mass. The salts do not harm the couple in the least, but the same method cannot, of course, be used with metallic substances.

When the naked couple is available, a piece of, say, 0·9 per cent. carbon tool steel, whose critical temperatures on heating have been determined, can be used over and over again, if a hole is bored to receive the end of the couple. The piece of steel containing the couple should be placed in a small clay crucible, and may be heated either on the smith's hearth or over a brazier's lamp, but always under the same conditions. A piece of steel prepared in the manner indicated has an advantage over most other substances which might be used for calibrating pyrometers. It can easily be obtained in any desired quantity, and it can be replaced without trouble. It is true that only a very limited range of temperatures can be checked in this manner, but the range for most purposes of heat treatment is the only one that is of any importance.

As this simple method of checking the indications of a couple has been discredited, the following results are of interest: An observation was made with an ordinary naked couple and portable indicator by four persons at different times. The readings at which the halt on heating occurred were reported as 739° C., 742° C., 741° C., and 743° C. respectively. With an arrangement especially designed for making thermal curves the halt occurred at 740° C.

The calibration of industrial pyrometers, whether carried out in the works or by the instrument maker, may be accomplished, as we have seen, by means of substances whose melting points, or rather freezing points, are fixed

and easily observed. It is obvious, therefore, that the temperature of a furnace which could liquefy one of these substances would be higher than its known melting point; and that of two substances, if one were melted and the other not, then the temperature of the furnace under observation would lie somewhere between the two. The Seger cones which for many years have been used in pottery kilns are well-known examples of this kind of temperature indicator. Seger cones, however, do not melt right out, but gradually soften and fall over at temperatures which are either higher or lower according to the rate of heating. Fusible metallic alloys and pure metals have been used for similar purposes though only to a limited extent (except for fusible safety plugs) on account of the readiness with which they oxidize. The systematic use of the fusibility of salts of the metals for temperature determinations under practical conditions has been tried with some success.

FIG. 60.—Sentinel pyrometer.

SENTINELS.

The Sentinel pyrometer (Fig. 60) is a small cylinder measuring about 20 mm. × 12 mm. made from salt mixtures of definite melting points.

These are not subject to oxidation, though, of course, only those salt mixtures are available for the purpose which neither dissociate nor become violently corrosive in the molten state. If a Sentinel having a melting point of, *e.g.*, 770° C. be allowed to rest in a small porcelain saucer in any heated area, it will retain its shape as long as the temperature does not exceed 770° C. When 770° C is exceeded the Sentinel melts and remains fluid in the saucer.

If, however, the temperature falls again below 770° C. the fluid material sets, but will continue to pass from the

liquid to the solid state and *vice versâ* as often as the temperature falls below or rises above 770° C. If now a second Sentinel having a melting point of 800° C. is placed in the same area, and the former melts and remains fluid whereas the latter remains erect and solid, then obviously the temperature lies between these two extremes. In this simple way the temperature of a suitably fired furnace can

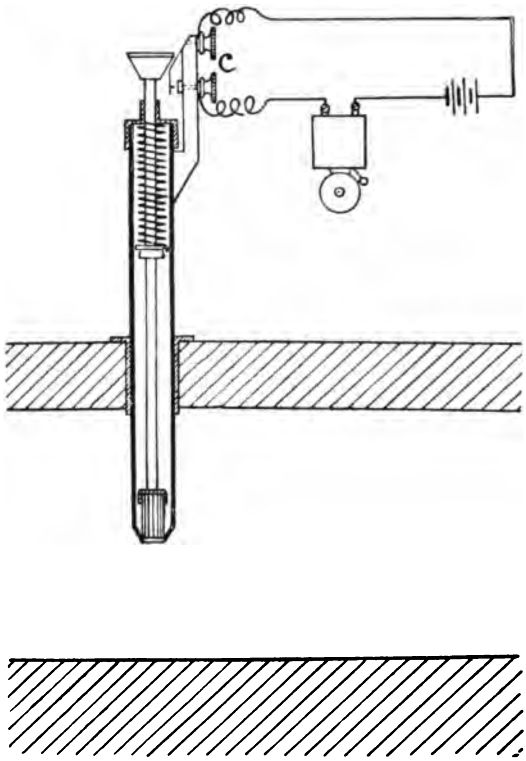


FIG. 61.—Sentinel indication apparatus.

be measured and maintained with any reasonable degree of accuracy.

CLOSED BOXES.

To indicate a maximum temperature inside an annealing box or at any part of a closed furnace, the instrument shown diagrammatically in Fig. 61 may be used with a Sentinel.

It consists of a wrought-iron tube partly closed at the lower end; inside is a rod to which one of the small Sentinels can be attached, and at the upper end of the rod

is a spring which causes pressure to be exerted on the Sentinel. As soon as the desired temperature has been reached the Sentinel melts, the inner rod falls, makes electric contact at C, and causes a bell to ring.

Sentinel Paste. Mixtures of salts, after being melted together and ground to a very fine powder, may be made into an adhesive paste with vaseline, and applied to many purposes for which no ordinary form of pyrometer is available. In the smith's hearth, for example, a tool may be heated to low redness and smeared near the point with a small portion of a paste whose melting point is, say, 770° C. The tool is then reheated, directly in the fire or protected from the cokes by a piece of scrap, wrought, or cast iron piping, until the white mark left by the thin layer of the salt mixture fuses and disappears. This indicates that the steel itself has nearly reached the desired temperature and may be quenched. It is quite easy in this manner to harden a small tool either in the shop or mine with nearly the same degree of accuracy as can be attained with the usual equipment of a good hardening shop.[1]

Magnetic Changes. For some years use has been made of the fact that at the critical thermal change-point in all ordinary carbon steels, the material also loses its magnetic properties and ceases to attract a magnet. This coincidence is not so well marked in certain kinds of alloy steels. Any form of small magnet can be used in the furnace to determine when the attraction ceases, but as the different parts of an object do not generally heat up at the same rate, owing to variations in thickness, it is quite clear that serious error can only be avoided by paying careful attention to this point.

A balanced or suspended magnet in the hardening shop somewhere near the furnace may be found a very useful touchstone. A magnet may be used for quite small subjects which can be heated in a flame suspended on the prongs. As the magnet loses its properties if heated to redness, it is advisable to use detachable prolongs made from soft steel or ingot iron. A special form of this device has been introduced as Taylor and Mudford's Patent.

[1] The sole makers of these "Sentinel" salt mixtures are the Amalgams Company, Ltd., of Sheffield.

XII

CASE-HARDENING

THE object of case-hardening is to carbonize the surface of mild steel, in places or all over, so that on quenching it may become glass hard, and at the same time preserve a core of tough, flexible material. The casing and the core may best be considered separately.

The oldest[1] commercial application of the principle of case-hardening is furnished by the manufacture of cemented bar iron or blister steel, which is still used for making high-class cutlery and a few other purposes. The operation consists of heating bars of Swedish wrought iron to high temperatures in closed boxes, between layers of wood charcoal, for a shorter or longer period, according to the degree of carbonization required. The modern case-hardening operation is in all respects similar in kind to this, but quicker carbonizing reagents than wood-charcoal are used, and exact temperatures are more closely adhered to.

FORMING THE CASE.

From a previous consideration of mild steel on p. 28, we have seen that those areas which contain carbon, *i.e.* the pearlite areas, undergo a change at about 750° C., and at somewhat higher temperatures these same carbonized areas begin to enlarge or diffuse into their carbonless iron surroundings. For the same reason any form of carbon pressed closely against the surface of pure iron will combine with it, and in the combined form penetrate into it if the prevailing temperature is not lower than about 750° C. If the temperature does not exceed 850° C., the penetration will increase with the time, but the *amount* of carbon in any portion of the surface will not exceed one per cent.; that is to say, the surface on quenching will be able to assume a

[1] Exception must be made of files, to which a process (perhaps unconscious) of case-hardening was applied more than a thousand years ago.

maximum degree of hardness and toughness combined, and will contain no excess of carbon as cementite.

If, however, the temperature be increased to 1000° C., then in six or eight hours the casing will be 2 or 3 millimetres thick, and in course of time the amount of carbon will so far increase that, on cooling, the excess over

FIG. 62*b*. FIG. 62*a*.
Composite section of case-hardened bar before and after quenching.

and above 0·9 per cent. will separate out as free cementite in the form of cell walls or interlacing needles, as shown in Figs. 6 and 7.

A composite picture made from a section of such a bar is reproduced in Fig. 62*a* in the unhardened and in Fig. 62*b* in the hardened state.

In these figures, which are copied from a paper by Bannister and Lambert,[1] the free cementite has assumed the form of interlacing needles, but generally in commercial articles, if it exists at all, it assumes the cellular form.

FRECKLED CORNERS. However it may occur, the presence of free cementite in case-hardened objects, with few exceptions, is a disadvantage, as the hardened surface has a great tendency to splinter under shock, and may even crack on hardening, as shown by Fig. 62*b*, along the boundary to which the free cementite penetrates. The presence of free cementite is due to the casing operation having been conducted at too high a temperature, and it may usually be detected in the coarse fracture of a broken section along the edges, and especially about the corners. This appearance, which is represented by Fig. 63, associates itself as a matter of experience with articles which are apt to shale or crack, and is known colloquially as "freckled corners." The entire object is disposed to brittleness, because the core as well as the casing is deteriorated by the use of a needlessly high temperature.

FIG. 63.—Freckled corners.

No hard and fast rule governing the temperature at which the casing becomes supercarbonized can be stated. It may occur at temperatures about 875° C., on the one hand, and, on the other hand, it may require, in the same time, a temperature as high as 1000° C., depending on the kind of case-hardening reagent used. This fact explains apparent contradictions on the point amongst authorities, some of whom have investigated the subject only under one particular set of conditions. Guillet, who exposed the same kind of iron for eight hours at 1000° C. to the case-hardening influence of five different mixtures, obtained amounts of carbon in the first quarter of a millimetre of casing which varied from 0·94 to 1·32 per cent., and in the

[1] *Journ. Iron and Steel Inst.*, 1907, vol. ii. p. 114.

second quarter of a millimetre from 0·77 to 1·19 per cent. The greatest amount was introduced by a mixture consisting of sixty parts of wood-charcoal and forty parts of barium carbonate.

PENETRATION.

The influence exerted on the depth of penetration by variations in time and temperature are plotted in Fig. 64 from the results of Guillet's observations as presented by Bauer.[1] The full line represents the relative penetration at 1000° C. for varying lengths of time, and the broken line the relative penetration during eight hours at varying

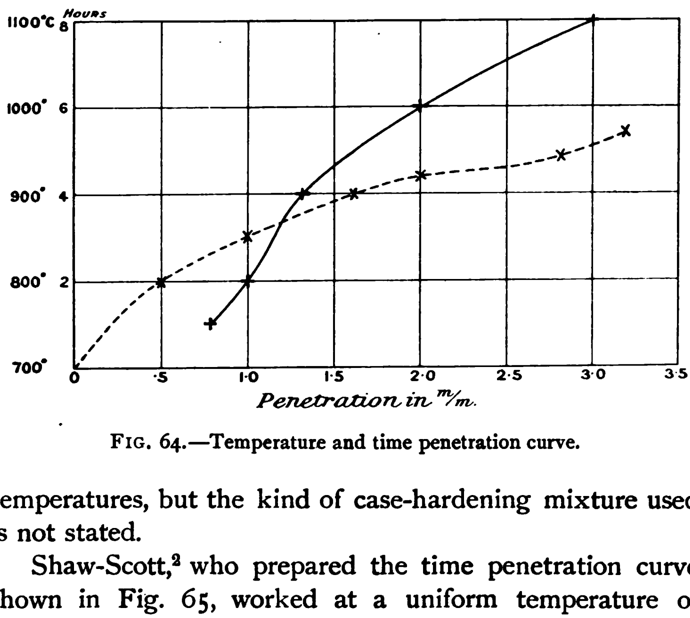


FIG. 64.—Temperature and time penetration curve.

temperatures, but the kind of case-hardening mixture used is not stated.

Shaw-Scott,[2] who prepared the time penetration curve shown in Fig. 65, worked at a uniform temperature of 900° C., and determined the efficiency of the wood-charcoal barium carbonate mixture in comparison with burnt leather and wood-charcoal.

Although the rapid penetration effected by a mixture of beech or oak-wood charcoal with forty per cent. of barium carbonate has caused it to be frequently recommended, it is necessary to remember that at a temperature of 900° C. or beyond, the amount of carbon it introduces into the casing exceeds 0·9 per cent., which for general

[1] *Stahl und Eisen*, 1904, p. 1058.

[2] *Journ. Iron and Steel Inst.*, 1907, vol. iii. p. 120.

purposes is the ideal amount that can be safely exceeded only when a casing is subject to hard rubbing wear without shocks. The most widely used material is charred leather, for which temperatures between 900° and 950° C. are suitable. Wood charcoal, or mixtures of wood and bone charcoal, can be used at temperatures between 950° and 1000° C. without fear of forming a supersaturated casing, but their penetrative effect is relatively small, and they have no recommendation, save low cost. Bone charcoal used alone is much more effective than wood charcoal, but

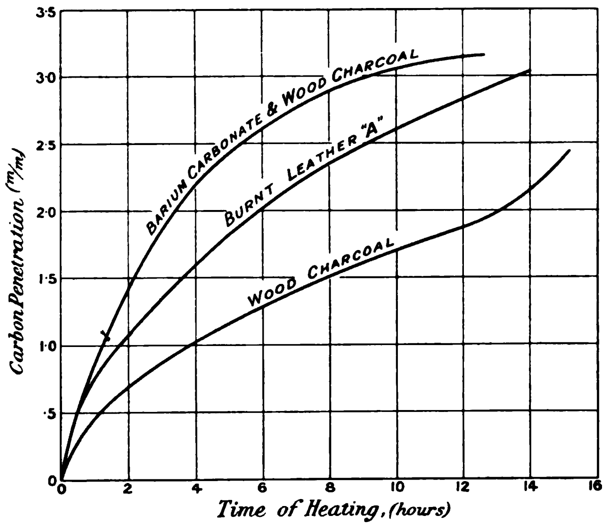


FIG. 65.—Time penetration curve—Shaw-Scott.

at high temperatures (1000° C.) it may introduce phosphorus into the surface of the steel, or even cause it to blister.

SOLID REAGENTS. It is possible to cement the surface of hot iron by pressing pure carbon against it, so that by a direct reaction between the carbon and the iron the two will combine. But in all forms of industrial case-hardening the actual carbonization is due to the hot gases which are either liberated by the case-hardening compound or formed by a reaction between the occluded air and the powder. This statement can be easily confirmed. If a piece of a square bar of mild steel be packed in sand almost to its upper surface, and then, after covering the sand with asbestos

paper the box be filled with some solid case-hardening mixture—say charcoal and barium carbonate—and fired, it will be found that the carbonization has taken place not only on the upper face of the bar, but also to an equal degree on every side of it. Fig. 66 represents such a bar, which after treatment was polished and etched on a transverse section.

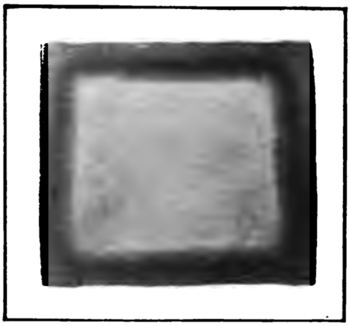


FIG. 66.—Section of square bar in contact with case-hardening powder on the upper surface only.

A simple if not very accurate means of picturing the process whereby those portions of a bar not in direct contact with the powder become cased is to assume that the carbon monoxide formed in the box becomes decomposed as follows:—

$$2CO + 3Fe = Fe_3C + CO_2,$$

the CO_2 in turn being readily reduced again by the excess of charcoal to CO. This reaction by no means explains everything, nor, for the matter of that, do any others with which we are acquainted. The necessity for a gaseous medium seems, however, to be beyond doubt, and possibly the absence of occluded gases is partly the reason why the harder forms of carbon, such as anthracite and coke, are such poor case-hardening materials.

GASEOUS REAGENTS.

From the above considerations it follows that gases pure and simple may be used for case-hardening purposes. There exists, however, the greatest possible variation of opinion respecting their value. Thallner in his book on Tool Steel says that "illuminating gas conducted over the surface of red-hot steel exerts a cementing effect of great energy"; whereas Olsen and Weissenbach in a paper read before the American Institute of Chemical Engineers in 1909 state that no cementing effect was observable after four hours at 1500° F. (816° C.) unless the gas was first passed through a solution from which it could take up free

ammonia. It frequently happens that such differences are more apparent than real, and are due to some variation in the mode of working, which at first sight may seem relatively unimportant. As illuminating gas is by far the most convenient material to use in small plants, we may refer to some experiments made by R. Bruch recorded in the first volume of reports issued by the Metallurgical School in Aachen. He found that the cementing action rose very slowly from about 700° to 900° C., and then more rapidly up to 1050° C., and very suddenly at 1100° C., as may be seen from the following table, which gives the percentage of carbon in each separate layer half a millimetre in thickness turned from a round bar after exposing it to gas at the given temperatures for seven hours.

Temperature.	Per cent. carbon in successive 0·5 mm. layers.				
	1.	2.	3.	4.	5.
700° C.	0·096	0·045	0·036	—	—
800° C.	0·210	0·105	0·048	—	—
900° C.	0·363	0·210	0·057	—	—
1000° C.	0·579	0·321	0·241	0·152	0·091
1050° C.	0·594	0·365	0·332	0·212	0·150
1100° C.	1·522	1·487	1·284	1·147	0·988
1150° C.	1·637	1·604	1·382	1·330	1·195

This table at once informs us why experiments made at different and perhaps unrecorded temperatures are apt both to confuse and mislead; there are, however, other experiences of a contradictory nature respecting the use of gaseous reagents for which no explanation has yet been found. Other gaseous substances in commercial use include acetylene, petrol or petroleum vapour, and carbon monoxide. All of them, except the last, are supposed to be more effective if they are led through a solution containing ammonia, or otherwise are partly saturated with ammonia gas before entering the furnace. The hydrocarbon gases readily deposit solid carbon in the case-hardening vessel, either as a pulverent mass or as compact graphite, according to circumstances, and this may at certain stages adhere

firmly to the objects, and either retard or prevent further carburization.

Objects which require to be case-hardened should have clean surfaces. A thin layer of oil is not harmful, but rust or contact with clayey matter must be avoided. If any portion has to be kept soft, it may be wrapped with asbestos paper and smeared over with clay, or in some other way protected from contact with the case-hardening powder and the gases it evolves. Certain elements in the steel increase the rate at which cementation proceeds, and others retard it. In the former category, according to Guillet, we must place manganese, chromium, tungsten, and molybdenum; and in the latter nickel, titanium, silicon, and aluminum. This classification would probably vary somewhat according to the kind of casing medium used.

HEAT-TREATMENT.

The object which we may presume has been carbonized to the required depth and not supercarbonized, and therefore quite free from freckled corners, may be cooled in the furnace, or taken at once from the box. But it has been exposed to 900° C. for six or eight hours, and both casing and core are obviously overheated. We could not expect, therefore, a first-rate result if it were quenched straight from the box, any more than we should expect tool steel to be at its best after such treatment . . . . (1).

We may allow the object to go cold, and then heat again to a temperature from which quenching will confer glass hardness—say 760° to 780° C.—but we should still have an undesirable core, and only improve the casing up to the standard of a bar of tool steel which had been badly forged; that is to say, finished at too high a temperature, and apt therefore to crack or be brittle after subsequent hardening . . . . (2).

We may, on the other hand, either heat the object rapidly to 900° C.,[1] and allow it to remain at that temperature only fifteen to twenty minutes, and then cool in the air, and afterwards reheat for hardening . . . . . (3).

Or reheat to 900° C., as in (3), to refine the core, then,

[1] The temperature may be increased to 950° C. if the mild steel used contains less than 0·20 per cent. carbon.

after cooling, reheat again to 800° C. to refine the casing; and, finally, again from the cold reheat to 760° to 780° C., and quench out in water . . . . (4).

If the heating according to process (3) is not needlessly prolonged, the casing as well as the core is very much improved, and perhaps the bulk of the work done under commercial conditions is treated in this manner. In some factories the objects are quenched in oil instead of being allowed to cool freely in air, but this is a modification of doubtful value.

THE SOFT CORE.

The condition of the soft core is of great importance in articles which are subject to rough usage. If it were left in the coarsely crystalline state, as it would be after process (1) or (2), then any small defect in the casing which formed a crack would travel through the mass without much hindrance. As a means of measuring the facility with which a crack will travel through material, use may be made of the impact test carried out on bars provided with a sharp notch. In this way, more clearly than by the ordinary form of tensile testing, the advantage of the well-refined core can be demonstrated.

This test can be made qualitatively with a hand hammer on bars which have been notched with a triangular saw file and then fixed in a vice. The effort required to break off the notched piece and the appearance of the fracture are both instructive and convincing, although the results cannot be expressed in concrete figures. If a quenched bar be bent sharply in the hardened state the casing will split in several places in parallel rings, and the core will stretch without breaking if it is tough; whereas if it is crystalline and brittle it will break off short. The result depends very much on the rate at which the bar is bent, and the test is not so reliable as a notched bar impact test carried out on the core only.

CASING AT LOW TEMPERATURES.

The need for any of the above forms of thermal treatment after the casing operation and previous to water-quenching is demanded entirely by the overheating of the material during the casing operation. If this operation could be carried out commercially at 800° C. or below, no great advantage would be gained from the intermediate

thermal treatment, and it could be dropped. The wood-charcoal barium carbonate mixture appears to come nearer to this ideal than any other case-hardening powder at present in regular factory use. It can be successfully used at 850° C., and the steel objects may then be directly hardened by quenching from 760° C. with better results than are possible after the same number of operations on more highly heated steel.

CASING TOOL STEEL.

From the causes discussed on page 17, it occasionally happens that tool steel is decarbonized on the extreme surface of sections rolled to finished sizes. In order that pieces cut from such bars may be given a perfectly hard surface by water-quenching it is necessary to smear them with some cementing material which will take effect in the hardening furnace. Such substances are usually mixtures of various ingredients from amongst the following: soot, horn meal, resin, yellow prussiate of potash, common salt, tartaric acid, tar, and flour. The salt fuses on to the surface of the steel, and acts as a vehicle only for the active case-hardening ingredients. Compositions made from some of the above-mentioned substances are sold and used to avoid scaling and decarbonization during heating operations.

CYANIDE HARDENING.

A very thin casing can be given to small articles by heating them up to the required hardening temperature in a bath of potassium cyanide. In this way an extremely hard surface is quickly obtained on objects which are too thin to keep their shape during the ordinary case-hardening procedure. But the fumes given off from the molten cyanide are exceedingly poisonous, and every possible precaution needs to be taken to avoid personal injury; on that account its regular use is undesirable.

XIII

ALLOY STEELS

THE foregoing pages refer chiefly to ordinary tool steel; *i.e.* iron carbon alloys containing up to two per cent. of carbon; one or two tenths per cent. of silicon, which is unavoidably picked up from the crucible; two to four tenths per cent. of manganese, which is intentionally added, and only unavoidable amounts of sulphur, phosphorus, arsenic, and copper. The manganese may be purposely increased up to 0·6 per cent. in material, which must be oil-hardened, and the silicon may be increased to about 0·5 per cent. in steels required to take a high polish or in tungsten steels which are intended for cutting very hard materials. The influences exerted on the properties of steels by the alloyed metals, either singly or in combination, form a problem which can be approximately solved only by long and tedious observation and careful experiment on the part of both the steel-maker and user. The subject can be discussed here only so far as it intrudes itself into the general practice of tool-making. From this standpoint only two elements—tungsten and chromium—taken singly and together, need to be specially mentioned.

TUNGSTEN STEELS.

The presence of tungsten in tool steel can be immediately detected, even in amounts as small as a quarter of one per cent. by the colour of the spark thrown off on pressing a corner of it against an emery wheel (see page 142). No other element produces the same effect, and none of the special elements added to steel mask this quite characteristic appearance; but the test is by no means quantitative.[1]

[1] Metcalf says: "As little as 0·10 per cent. tungsten will show a fine red line amidst a brilliant display of sparks, and it soon becomes possible to determine so closely by the streak the quantity of tungsten present that the ordinary analyses become unnecessary"!

The fracture of tungsten steel, even in the unhardened state, is much closer in appearance than carbon steel of the same temper and treatment. In the hardened state the fracture is quite porcelain-like when two or three or more units per cent. of tungsten are present. Tungsten steels may be considerably overheated without forming the coarse crystalline fracture formed in carbon steels, and also without becoming mechanically fragile and useless. In this respect it may be compared with any other kind of steel by simultaneously making Alling's test pieces as described on page 46. The ability of tungsten steel to resist at higher temperatures the formation of large crystalline structures is of the greatest possible use in high-speed steels, which must necessarily be hardened at temperatures sufficiently high to spoil absolutely an ordinary carbon steel tool.

Apart from high-speed steels, tungsten is a useful ingredient in tools which are intended to cut very hard materials, such as chilled rolls. On account of its keen and durable cutting edge, the steel is also used for taking finishing cuts both on hard steels and soft metals, such as copper. It also makes excellent hand punches, but it is too brittle to withstand heavy shocks.

If forged too cold tungsten steels have an unusual tendency to laminate at right angles to the direction of the final blows. This is generally observable only in flat sections, and might be ascribed to piping in the ingot, except that it usually runs through the entire length of the bar. If a bar which is laminated in the centre purely and simply on account of cold working be reforged into a square, all signs of lamination disappear, and the bar can be hardened without any defective centre being observable.

Tungsten favours the intensive hardening of steel and the depth to which the hardening effect penetrates below the surface. But it is less vigorous in this respect than is commonly supposed, and very much inferior to either chromium or manganese.

CHROMIUM STEELS.

Chromium steels are very tough in the annealed state, and on hardening, if properly hardened, they exhibit a fine fracture similar to that of tungsten steel, but not quite so

glossy in appearance. The hardening effect also penetrates much deeper on account of the presence of chromium, and for this reason chromium steels are frequently used for making hardened steel rolls. At the same time there is, of course, a greater tendency for cracks to form through sharp angles and for square corners to spring off. If overheated, the fracture readily becomes coarse and the material breaks off short; in this respect chromium steels are quite as bad as ordinary carbon steels.

SELF-HARDENING STEELS.

If a steel containing a few units per cent. of chromium be heated at temperatures which ascend in stages from 800° C., and is then allowed to cool in the air, it becomes gradually harder, and finally, in small sections, becomes quite hard. That is to say the material possesses the "self-hardening" property when air-cooled from above a certain minimum temperature. The old form of "Mushet" steel was self-hard, owing to the amount of chromium or manganese, or both, which it always contained in addition to the tungsten. We are not able to say how far a steel containing no other special element besides chromium might be found to possess the properties of a "high-speed" steel as well as those of a "self-hard" steel if the overheating did not produce coarse crystallization and an edge too weak to bear the mechanical stress of cutting.

In their influence on the properties of steel, chromium and tungsten are in many respects complementary. The one provides what the other lacks, and taken together they are responsible for the remarkable properties of the modern high-speed steels.

HIGH-SPEED STEELS.

In considering modern high-speed steels it is necessary to modify many ideas gathered from the study of carbon steels. It does not follow, for example, that an increased amount of carbon necessarily makes a high-speed steel harder either after air or oil quenching; it may make it softer. Nor does it follow that the steel is harder the more quickly it is cooled; it may be softer. A modified form of this remark applies also to many of the air-hardening, nickel-chromium steels now being used in the motor trade. It is, however, without exception true that high-speed steels, as forged or cooled quietly in air from temperatures of about

900° C. and over, are hard and must be handled in all subsequent operations like bars of hardened steel. This property involves precautions which can perhaps be best discussed under separate heads.

FORGING. All heating operations on forged bars must be started slowly, to avoid clinking; this is not so important with annealed bars, because the soft material can extend under sudden stresses without breaking. The steel, even when hot, does not allow its shape to be readily altered, and is therefore in practice forged at higher temperatures than are required for carbon steels. It is necessary to forge the material thoroughly after it has been exposed for some time to the temperature of a reheating furnace, in order to destroy the coarse structure. It is sometimes said that high-speed steel cannot be overheated, but the statement is misleading. The crystalline grains increase in size at high temperatures in the same manner, if not with the same ease, as in carbon steels.

FLAKING. When high-speed steel has been soaked at high temperatures and insufficiently forged it exhibits a very characteristic scaly-looking fracture. This kind of fracture, which is spoken of as being "flaked," is a great annoyance to makers of drills and cutters, and is associated in their minds with a tendency to crack, in exactly the same manner as tools made from overheated or insufficiently forged carbon steels also crack. The flaked fracture cannot be distinguished after annealing, but it appears again on rehardening the annealed bar, and nothing short of reforging seems able to entirely suppress it. When forged bars are being ended in the steel warehouse, those exhibiting a flaked fracture should be rejected, on the same grounds as carbon steel bars would be rejected which show the coarse fracture of overheated steel.

CRACKING. All high-speed steel bars, after forging, are in the air-hardened state, and subject to the same possibilities of spontaneous fracture as water-hardened carbon steel of the same section. Flat bars can be forged with less danger of waste than square bars, and square bars with less waste than round ones, for reasons already considered on page 79. It is advisable, therefore, that after forging, all tools, of

round section at least, should be put in a warm place where the interior and exterior portions will cool at about the same rate. This will minimize, if it does not altogether avoid, the formation of longitudinal cracks in the cold objects, which do not exist in the heated state and are not directly due to cold working.

ANNEALING. As annealed bars are much safer to handle, the practice of supplying all sections of high-speed steel in the annealed state is extending. This enables the material to be sawn to the required lengths, which is less objectionable than breaking it cold or cutting it hot. The former may start small cracks, and the latter leaves the ends, at least, of the material in the hardened state. It may also happen, in handling large bars, that the smith thoughtlessly pulls damp fuel round the heated bar and starts in this way a number of small water-hardening cracks, which lead later to serious defects that cannot always be traced to their real source.

Practically all kinds of air-hardening steels can be softened by tempering, *i.e.* heating them to a temperature *below* that at which they would harden on quenching. If annealing, as distinct from tempering, is taken to mean slow cooling from a temperature *above* that at which the steel will harden on quenching, then obviously air-hardening steels can only be softened by annealing if the cooling is made to occupy so much time that the air-hardening tendency is suppressed; and even then the softened state may be partly due to the tempering effect, which comes into operation after the critical hardening temperature is passed.

The maximum degree of softness, as measured by cutting tests in the lathe, cannot be attained by tempering, nor can it be attained by slow cooling from *high* annealing temperatures so well as by the kind of compromise illustrated in the following paragraph.

A batch of one-inch cubes, made from high-speed steel, were cooled freely in air from 1100° C. to represent the condition of a forged bar, and were then tempered for a period of one hour at various temperatures, and either cooled in the air from these temperatures, or allowed during

a period of one and a half hours to cool down with a small muffle furnace. The figures given are the Brinell hardness numerals of the respective pieces.

	Cooled in Air.	Cooled in Furnace.
Works annealed . . .	—	196
Cooled from 1100° C. . .	555	—
Reheated to 500° C. . .	512	—
,, ,, 600° C. . .	477	—
,, ,, 700° C. . .	286	—
,, ,, 750° C. . .	277	269
,, ,, 800° C. . .	269	248
,, ,, 850° C. . .	444	207
,, ,, 900° C. . .	495	—
,, ,, 950° C. . .	—	235

Prolonged exposure to the annealing temperature is not necessary. The success of the operation lies in attaining a temperature adapted to the subsequent rate of cooling, but in no case exceeding 850° to 900° C.

The change in mechanical properties which air-hardening steels undergo, as they pass the border between tempering and annealing, is very interesting. Up to what may be considered the limiting tempering temperature the elastic limit and maximum stress of the steel fall together as the temperature is increased. Then the elastic limit drops, and frequently the reduction of area also drops, and the maximum stress rises. Finally, as the hardening temperature is passed, the elastic limit and maximum stress rise again together. The treatment most favourable to machining operations consists in heating the steel to the temperature which induces the lowest elastic limit, and cooling subsequently at a rate sufficiently slow to suppress the air-hardening tendency; that is to say, to keep down the maximum stress.

RED-HARDNESS.

When heated to 900° to 950° C. and quenched in oil, high-speed steel is quite hard. It is almost as hard to the file, presuming the carbon is above 0·6 per cent., as it can be made by quenching from, say, 1200° C.; but it is not equally effective as a cutting tool. On the other hand, a high-speed steel tool, which has been cooled somewhat

slowly from 1200° or 1300° C., will cut mild steel at great speeds for a long time. We are thus compelled to recognize two kinds of hardness, one of which resists abrasion by the file, and the other which resists the tempering effect of the heat generated in cutting. This latter kind, which has been called "red-hardness," is especially characteristic of high-speed steels, and is known to be to some extent independent of the amount of carbon in the steel, and the rate at which the tool is quenched.

QUENCHING. It is not uncommon to find in air-hardening steels, other than those used for cutting purposes, that the hardness—as measured by the more conventional means, *e.g.* the Brinell Ball Test or the tensile machine—is equally great, and sometimes greater, after air-hardening and tempering, as after oil-hardening and tempering. This applies also to some kinds of high-speed cutting steels, both so far as hardness and red-hardness are concerned, and thus allows a latitude in the manner of quenching which can be turned to good account.

So far as the simpler forms of lathe tools are concerned, it may be immaterial whether they are quenched in air, in oil, or in water; but such tools as twist drills, reamers, and milling cutters, cannot be cooled throughout at a sufficiently uniform rate unless they are cooled somewhat slowly, and hence cooling in the air, or in hot oils, or in molten lead or salt, is less dangerous, and may be, as we have seen, equally as effective as water quenching. So far as we are aware, the effective life of a tool is not greatly increased by water quenching, whereas the danger of cracking is increased almost to a certainty in any object save the simplest forms of tools.

HIGH HEAT. The temperature to which high-speed steels must be raised to confer on them the maximum degree of red-hardness and cutting efficiency, depends to some extent on their composition. The change to be effected in their structure is of the nature of a diffusion, or solution of the separate constituents into one homogeneous substance, which, as seen under the microscope, is practically structureless.

Compare, for example, Fig. 67, illustrating the micro-

structure of the annealed, and Fig. 68 the micro-structure of the hardened, material.

FIG. 67.—Annealed high-speed steel.

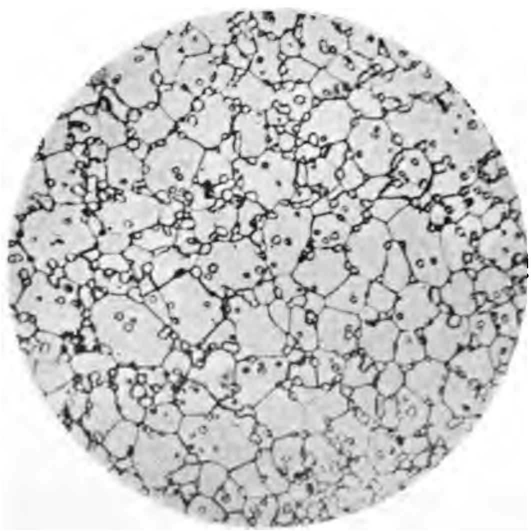


FIG. 68.—Hardened high-speed steel.

This change in structure takes place quickly at

temperatures of about 1200° to 1300° C., and is supposed to coincide with the formation of a double carbide of chromium and tungsten dissolved in the iron. In order to make the high-heat treatment as uniform as possible, it is advisable to first heat the tool thoroughly, and without haste, to 850° C. or 900° C., and finally bring it as rapidly as possible to the higher temperature in a non-oxidizing atmosphere. The rapid heating is essential.

OVER-HEATING AND OTHER TROUBLES.

The notion that high-speed steel cannot be spoiled by burning or over-heating is a wrong and costly one. Any person who has had an opportunity of hardening high-speed tools made from the same material, and testing them crucially on the lathe, knows that most startling discrepancies creep in during hardening. A great deal of labour has been spent in making comparative tests of steels containing varying percentages of carbon, chromium, tungsten, molybdenum, etc. Every metallurgist realizes the value of a series of such tests, and practically every well-known steel-maker has done work in this direction. From this mountain of labour there has appeared a few reliable general conclusions, together with a mass of contradictory evidence, which suggests that many experimenters failed to clearly realize the nature of the problem.

Take the following example of experiments made at a well-known public testing station to determine the relative value of steels A, B, and C. A tool made from each bar was forged, and then hardened by the same man in the same coke-fired furnace. The tools were ground each time to exactly the same angles, and all tested in the same lathe on 0·75 per cent. carbon steel, running at the circumferential rate of seventy-six feet per minute. The figures represent the number of minutes the respective tools were in use before they refused to cut.

Mark of steel.	A.	B.	C.
As originally prepared	4·40	3·00	—
After regrinding only	6·66	31·25	—
Rehardened the next day . . .	14·60	13·20	30·81
Reground again	10·30	15·95	11·17
Rehardened the third day . .	8·90	25·10	3·00

If testing conditions cannot be duplicated, then the results must obviously be unreliable. The number of variables which influence the behaviour of cutting tools is so great that a complete solution of the problem of selecting the best kind of steel—if such a thing can exist—has not yet been reached.

In instances such as that just quoted, the operation which of all others is most important, *i.e.* the hardening, was apparently the least uniformly carried out. It is well known that chromium-tungsten steels very readily scale, and are easily decarbonized in consequence. They also very readily take up carbon at the high temperature to which they are exposed, if other circumstances are favourable, and either of these possibilities could operate on tools hardened successively from the same smith's hearth, and, in consequence, cut better or worse after grinding. Again, a bar of high-speed steel, which has remained very hot or nearly molten for a short time, if split longitudinally after hardening (see p. 46) will show at the extreme point a spongy or striated structure, and behind that a structure varying from coarse to fine as it recedes from the hottest part. To minimize this sponginess tools are sometimes lightly hammered before cooling. So long, however, as the spongy or striated portion remains, the cutting edge of the tool is mechanically weak however hard it may be. Fig. 69 is a micro-photo of a piece of high-speed steel which has been kept too long at high temperatures. The separate crystals are many times too large, and have already begun to break away from each other.

In order to obtain comparative results a fixed final temperature, a uniform rate of heating, and a neutral heating medium are necessary. The first English patent specification relating to modern high-speed steel tools (No. 10738 of 1900) recommends a protective covering "which at a high heat will melt and cover the working part of the tool with a film, which will exclude air and other gases which might injuriously affect the surface of the tool." Such a protective coating may be applied as follows: after the tool has been slowly heated to redness, sieve over it

powdered borax glass which at once melts and adheres. Then, in the same way, cover the point of the tool with powdered glass, and expose to the high-heat treatment as usual. The flux is easily removed after cooling, and leaves the surface of the steel clean and unchanged. A number of liquid anti-scaling mixtures into which the tool may be dipped are also in use.

HIGH-SPEED STEEL HARDENING FURNACE.

Furnaces for hardening high-speed steel tools are made by all the manufacturers mentioned on page 88 in varying designs for special purposes; there is no need, therefore,

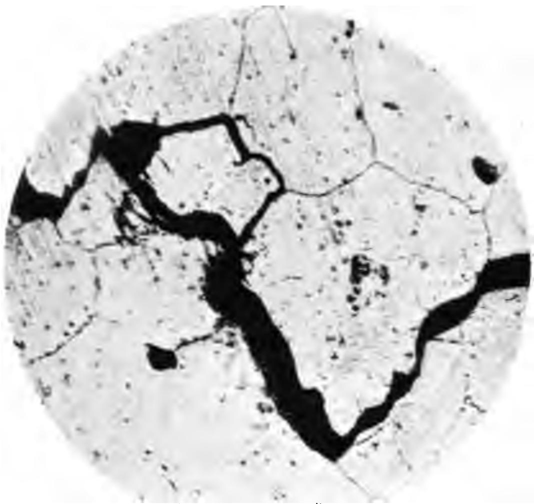


FIG. 69.—Burnt high-speed steel.

to describe them here. In order to exclude atmospheric oxidization altogether, a bath consisting of molten barium chloride, heated to the required temperature by an electric current, has been introduced. It has all the advantages of a liquid bath, and appears to be quite satisfactory for small articles, such as twist drills treated in large quantities. But the first cost of the apparatus is high, and on that account is sometimes replaced by a receptacle for the barium chloride, such as a graphite crucible, heated with gas or cokes. A gas-heated barium-chloride bath is not highly satisfactory. The oxidization at the surface of the bath

soon soils the melt with floating particles of iron oxide, which may adhere to the tools, and at the prevailing high temperature cause soft spots. An attempt to avoid this oxidization by a layer of charcoal, or retort carbon, spread over the surface of the barium chloride, causes the drills or other objects to become strongly carbonized and pit where they are in contact with the upper layer of the melt. The barium chloride used should be pure, or at least quite free from sulphur compounds, as these, in the molten state, readily attack the surface of steel objects.

GRINDING.

The possibility of starting and extending cracks by rash grinding is discussed on page 82. The subject is especially important in relation to high-speed steels, because many failures can ultimately be traced, if trouble enough is taken, to this obscure cause. Very fine cracks existing in ground objects can sometimes be made visible only by suitable forms of etching. Unless exposed in this way their existence might be unsuspected until the tools had been in use and possible causes of the defects, then for the first time observable, had increased.

Hardened steel cracks under the local heat of friction, because the heat is not dissipated fast enough and sets up local expansions which the rest of the material is too rigid to accommodate, just as thick glass will crack if held over the tip of a candle flame. If, however, the glass be slowly and carefully warmed it can ultimately be held in the flame with impunity, and, as a matter of experience, it is found that if tools are heated to 200° C. or more before grinding, the danger of cracking is minimized, if not entirely avoided.

APPENDIX

CUPPED WIRE

A VERY pronounced instance of failure due to hard centre, which has become more frequent since Siemens and Bessemer steels, which are necessarily cast in large ingots, have come into use for wire making, is known as "cupped wire." The wire breaks as it passes through the draw plates with a characteristic cup and cone fracture. If a piece of such wire be cut longitudinally, it will show a row of holes down the centre, and if it be etched it discloses a segregation of carbon, sulphur, and manganese right along the centre where the holes appear. All these features are seen in Fig. 70, which is an enlarged photograph of a section of a small screw which had been made from bright drawn rods.

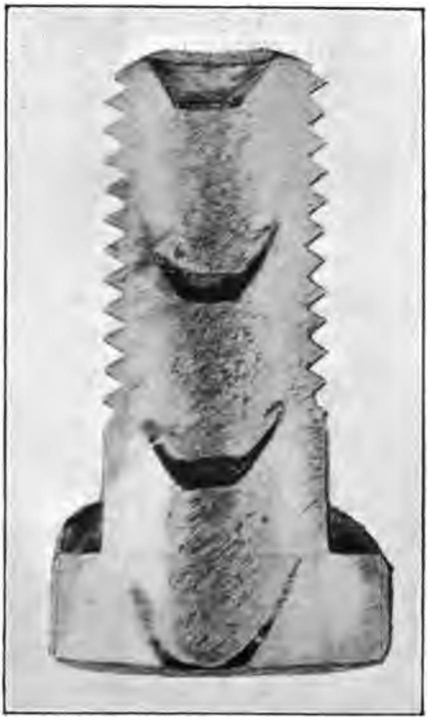


FIG. 70.—Cupped cold-drawn rod.

The cupped fracture is formed in passing the draw plates. The softer parts of the wire extend at a greater rate or to a greater length than the harder centre can bear without breaking. This defect is easily distinguishable from crushed centres due to improper forging which extend continuously over a fair length instead of being a break here and there. This kind of defect has been observed in cold-drawn material varying between half-inch bars and fine needle wire.

APPARATUS FOR MAKING THERMAL CURVES

An effective piece of apparatus for determining the critical points, and obtaining the form of the heating and cooling curves for most steels, is shown in Fig. 71.

A small sample of the steel under observation is machined to

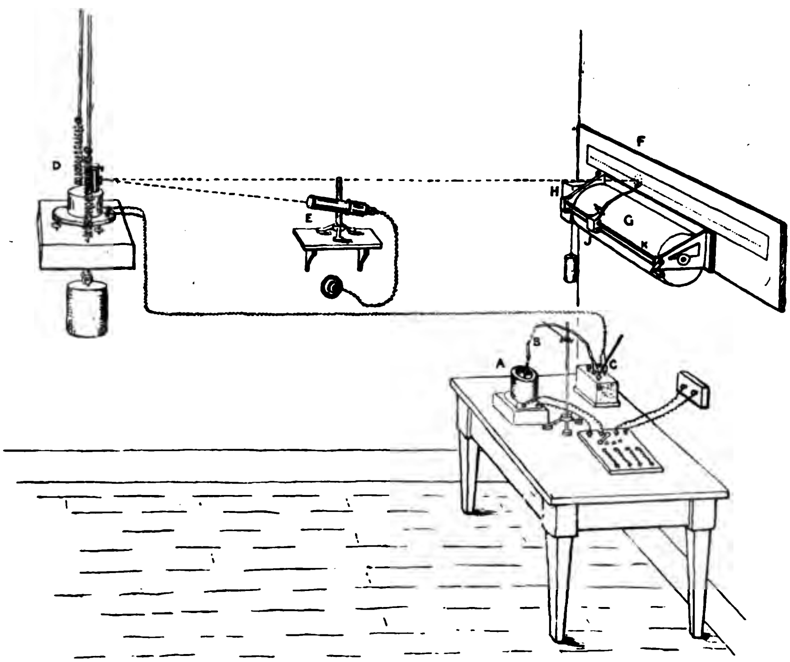


FIG. 71.

a size of about 10 mm. in diameter and 25 mm. high, and a 4-mm. hole drilled vertically down its axis to a depth of 15 mm. It may, however, have any other regular or irregular shape. This sample is placed upright in the centre of a small electrically heated furnace shown at A, and the electric current supply so arranged as to heat

the specimen from cold to 900° C. in about twenty minutes. The "hot junction" end of a platinum platinum-rhodium thermo-couple, B, is then inserted to the bottom of the hole in the test piece. From the "cold junction" of the thermo-couple at C, close to which is placed a mercury thermometer, electric connecting wires are led to a moving-coil mirror galvanometer, shown placed on the suspended antivibration arrangement at D. The mirror of this galvanometer reflects a ray of light from the Nernst lamp telescope at E on to the scale at F, this scale being marked along its length in millimetre divisions. The exact centre of the moving spot of light on the scale is indicated by means of a fine hair line being drawn across the front of the telescope lens at E, and this line, coming into exact focus along with the spot of light on the scale, enables very small movements to be closely followed. The thermo-couple being previously calibrated by a method similar to that described on p. 110. A series of points are obtained on the millimetre scale corresponding with known temperatures of the thermo-couple hot junction, and rising or falling temperatures of the steel sample, or shown clearly by the position of the centre line of the spot of light on the scale.

In order to record these movements, and so obtain the "Heating and cooling" curve, a drum, G, carrying a sheet of paper on its surface, is made to revolve slowly and uniformly by means of clockwork, H. Along the front of this drum is a small pencil carriage, J, so mounted that horizontal movement along the drum can be given to it by means of the screw K, when the crank angle fixed to the right-hand extremity of the screw is turned by the hand of the observer. A small pointer, forming an extension to the pencil carriage, is carried above the drum, and travels close against the face of the scale F, so that the observer can quite easily keep this pointer, and consequently the position of the pencil on the drum, exactly corresponding to the centre of the spot of light during its movement up or down the scale. In this way a complete curve, such as that shown by Fig. 24, on p. 36, is obtained. No extraordinary amount of care is needed to keep the pencil extension and the cross-wire image superimposed; it is, however, much easier if a disc, on which a broken line is ruled, be attached to the end of a pointer moving over the face of the scale. This broken line is made continuous by the image of the cross wire, and kept continuous by moving the pencil carriage at a suitable rate along the drum.

GRINDING SPARKS

SOME observant mechanic, grinding one of the Mushett-steel tools, which were introduced about 1870, must have first noted the characteristic colour of the spark thrown from the grindstone. This test appears to have been known for some time in many machine shops, and used to distinguish a self-hard tool when such were comparatively rare. The distinctive colour of sparks is more pronounced from an emery wheel than an ordinary stone, and it is found that less than one-half of one per cent. of tungsten can be easily detected in this way.

But the spark gives also other useful information. If a shower of sparks from an emery wheel is allowed to strike a glass plate a certain number stick (see Fig. 72). These have two different forms; the first are rounded blobs which suggest molten material, and the second are curled pieces of metal, similar to steel filings. When revolving at a high speed, an emery wheel removes minute portions of metal, and whirls them quickly through the atmosphere. The heat generated in effecting their separation raises them to incandescence and starts oxidation, which is easily kept up by a plentiful supply of oxygen in the atmosphere. In the case of pure iron the oxidizing mass ultimately fuses and forms a pear-shaped tail at the end of the incandescent ray (Fig. 73). In the presence of carbon, however, which is readily oxidizable, the oxidized envelope of the molten bead reacts violently with it, and produces a comparatively large volume of carbon dioxide gas, which in escaping from the bead breaks it up into radiating lines. As the speed of the reaction between the oxidized iron and the carbon of the steel, and also the amount of gas formed, depend on the carbon content of the steel, the explosive sparks produced under like conditions should vary in number or degree with the amount of carbon in the steel (see Fig. 73).

It has been claimed that the spark enables steels to be distinguished which vary amongst themselves by less than 0·05 per cent. carbon. This seems an extravagant demand to make on a

FIG. 72.—Sparks caught on glass plate.

FIG. 73.—How sparks vary as carbon increases.

test which is exposed to a number of unavoidable variations in shop practice. It may, however, safely be said that the sparks given by wrought iron, mild steel, and high carbon steel, as illustrated in Fig. 73, are sufficiently distinctive to be recognized and used for placing unknown materials into these groups, and for settling with little trouble such questions as to whether an article is all steel or welded. Its most frequent use, however, will continue to be associated with the characteristic red spark, obtained from steels containing tungsten; no other special element used in steel-making gives a spark by which its presence amongst any combination can be distinguished. The accuracy of the test is of course greatly increased by operating in a darkened room, and with one and the same wheel under standardized conditions.

It is interesting to note that use was made of the sparks thrown off by an ordinary grindstone, more than one hundred years ago. In his "Traité du fer et de l'acier" (Paris, 1804), General Jacques Charles de Manson sets forth a number of conclusions which may be drawn from the appearance of the spark.

HISTORY OF STEEL HARDENING

OTTO VOGEL contributes to *Stahl und Eisen*, 1899, p. 242, an interesting article on this subject, from which the following is abstracted; it deals chiefly with old ideas respecting the nature of hardening and the means used to accomplish it.

The origin of steel hardening cannot be traced; Homer refers to it, and was also aware of the colours which follow each other on tempering bright steel. Pliny the younger seems also to have been familiar with the art, as he informs us that "finer tools are usually hardened in oil rather than water which makes them brittle."

The old smiths were especially concerned about the fluid used for quenching, as they believed that something passed out of it into the steel. As early as 1558 records ascribe to the water of certain districts quite special properties. The manufacture of steel blades throughout the entire Middle Ages, and also nearer modern times, was regarded as secret. Apprentices had to swear fealty on oath, and dare neither leave the country, disclose their secret, nor teach the art once learned to any other than their own sons.

A Benedictine monk, Theophilus Presbyter, who lived in the second half of the ninth century, wrote a book in which he gives the following instructions for hardening files: "Char the horn of an ox, break it up and mix with a third part of salt; then lay the file in the fire, and when white hot strew the mixture over it. Heat over a quick charcoal fire, then remove it and quench uniformly in water; dry it afterwards over the fire." [1]

To harden tools for working stone, the same chronicler recommends that a three-year-old he-goat be taken and tied up for three days without food. On the fourth and fifth days it is to be fed on fern leaves and nothing else. On the following nights it is to

[1] This in principle is the method still practised in districts, *e.g.* in Russia, where some files are made from mild steel and require a coating to protect the teeth, and at the same time carbonize them to some extent.

be allowed to stand in a tub, and the urine, which runs through a hole in the bottom of the tub, falls into an empty bucket. When after two or three nights a sufficient quantity has been collected, the goat is released and the tools hardened in the urine. Also the urine of a red-haired boy hardens tools better than ordinary water.

The first serious investigation of the subject was undertaken by the French philosopher Reaumur, and though he naturally was greatly influenced by the prevailing point of view, his ideas bear a striking resemblance to some modern theories. He observed the increase in volume without a corresponding increase in weight, and concluded that the hardening of steel was entirely a question of changes in internal structure. Rinman, the Swede, continued these researches, and studied especially the tempering colours both on steel and other metals.

In 1740 Christian Polhem, also a Swede, in describing the process of converting iron into steel by cementation, gives also a number of hardening wrinkles which are still of value. For thin knives and shears he recommends quenching in molten lead. By the middle of the eighteenth century, a number of mixtures of salt, saltpetre, étc., were added to the hardening water in order to make the steel tough as well as hard; this vein of superstition appears to be not yet worn out.

Files appear to have been hardened two centuries ago very much as they are hardened to-day in districts where they are made from mild steel, *i.e.* they were coated with wet masses of horn dust and hoof parings, and then, after drying, heated and quenched. Watchmakers' files were supposed to be made hard and tough by quenching in a concoction of garlic made as follows: Cut the garlic into small pieces, cover with brandy and allow to stand for twenty-four hours in a warm place; then press out the liquor and preserve in closed bottles. Some quaint conceits about the quenching of steel in one liquor to make it hard, and in another to make it soft, are related by Roberts-Austen, "An Introduction to the Study of Metallurgy," 4th edn., pp. 138–140.

EQUIVALENT OF DEGREES CENTIGRADE IN FAHRENHEIT.

Degrees Centigrade ↓ →	0	10	20	30	40	50	60	70	80	90
	Degrees Fahrenheit.									
0	32	50	68	86	104	122	140	158	176	194
100	212	230	248	266	284	302	320	338	356	374
200	392	410	428	446	464	482	500	518	536	554
300	572	590	608	626	644	662	680	698	716	734
400	752	770	788	806	824	842	860	878	896	914
500	932	950	968	986	1004	1022	1040	1057	1076	1094
600	1112	1130	1148	1166	1184	1202	1220	1237	1256	1274
700	1292	1310	1328	1345	1364	1382	1400	1418	1436	1454
800	1472	1490	1508	1526	1544	1562	1580	1598	1616	1634
900	1652	1670	1688	1706	1724	1742	1760	1778	1796	1814
1000	1830	1850	1868	1886	1904	1922	1940	1958	1976	1994
1100	2012	2030	2048	2066	2084	2102	2120	2138	2156	2174
1200	2192	2210	2228	2246	2264	2282	2300	2318	2336	2354
1300	2372	2390	2408	2426	2444	2462	2480	2898	2516	2534
1400	2552	2570	2588	2606	2624	2642	2660	2678	2696	2714
1500	2732	2750	2768	2786	2804	2822	2840	2858	2876	2894
1600	2912	2930	2948	2966	2984	3002	3020	3038	3056	3074
1700	3092	3110	3128	3146	3164	3182	3200	3218	3236	3254
1800	3272	3290	3308	3326	3344	3362	3380	3398	3416	3434
1900	3452	3470	3488	3506	3524	3542	3560	3578	3596	3614
2000	3632	3650	3668	3686	3704	3722	3740	3758	3776	3794

TABLE FOR THE CONVERSION OF CENTIMETRES TO INCHES.

Centimetres.	British inches.	Centimetres.	British inches.	Centimetres.	British inches.	Centimetres.	British inches.
1	0·394	51	20·079	101	39·764	151	59·450
2	0·787	52	20·473	102	40·158	152	59·844
3	1·181	53	20·866	103	40·552	153	60·237
4	1·575	54	21·260	104	40·946	154	60·631
5	1·968	55	21·654	105	41·339	155	61·025
6	2·362	56	22·048	106	41·733	156	61·418
7	2·756	57	22·441	107	42·127	157	61·812
8	3·150	58	22·835	108	42·520	158	62·206
9	3·543	59	23·229	109	42·914	159	62·600
10	3·937	60	23·622	110	43·307	160	62·993
11	4·331	61	24·016	111	43·702	161	63·387
12	4·724	62	24·410	112	44·095	162	63·781
13	5·118	63	24·804	113	44·489	163	64·174
14	5·512	64	25·197	114	44·883	164	64·568
15	5·906	65	25·591	115	45·276	165	64·962
16	6·299	66	25·985	116	45·670	166	65·355
17	6·693	67	26·378	117	46·064	167	55·749
18	7·087	68	26·772	118	46·457	168	66·143
19	7·480	69	27·166	119	46·851	169	66·537
20	7·874	70	27·599	120	47·245	170	66·930
21	8·268	71	27·953	121	47·639	171	67·324
22	8·662	72	28·347	122	48·032	172	67·718
23	9·055	73	28·741	123	48·426	173	68·111
24	9·449	74	29·134	124	48·820	174	68·505
25	9·843	75	29·528	125	49·213	175	68·899
26	10·236	76	29·922	126	49·607	176	69·293
27	10·630	77	30·315	127	50·001	177	69·686
28	11·024	78	30·709	128	50·395	178	70·080
29	11·417	79	31·103	129	50·788	179	70·474
30	11·811	80	31·497	130	51·182	180	70·867
31	12·205	81	31·890	131	51·576	181	71·261
32	12·599	82	32·284	132	51·969	182	71·655
33	12·992	83	32·678	133	52·363	183	72·048
34	13·386	84	33·071	134	52·757	184	72·442
35	13·780	85	33·465	135	53·151	185	72·836
36	14·173	86	33·859	136	53·544	186	73·230
37	14·567	87	34·252	137	53·938	187	73·623
38	14·961	88	34·646	138	54·332	188	74·017
39	15·355	89	35·040	139	54·725	189	74·411
40	15·748	90	35·434	140	55·119	190	74·804
41	16·142	91	35·827	141	55·513	191	75·198
42	16·536	92	36·221	142	55·906	192	75·592
43	16·929	93	36·615	143	56·300	193	75·986
44	17·323	94	37·008	144	56·694	194	76·379
45	17·717	95	37·402	145	57·088	195	76·773
46	18·110	96	37·796	146	57·481	196	77·167
47	18·504	97	38·190	147	57·875	197	77·560
48	18·898	98	38·583	148	58·269	198	77·954
49	19·292	99	38·977	149	58·662	199	78·348
50	19·685	100	39·371	150	59·056	200	78·742

TENSILE STRESS.

Tons per Square Inch—Kilos per Square Mm.

Tons per sq. in.	Lbs. per sq. in.	Kilos per sq. mm.	Tons per sq. in	Lbs. per sq. in.	Kilos per sq. mm.
10·00	22,400	15·75	30·50	68,320	48·04
10·50	23,520	16·54	31·00	69,440	48·82
11·00	24,640	17·32	31·50	70,560	49·61
11·50	25,760	18·11	32·00	71,680	50·40
12·00	26,880	18·90	32·50	72,800	51·19
12·50	28,000	19·69	33·00	73,920	51·97
13·00	29,120	20·47	33·50	75,040	52·76
13·50	30,240	21·26	34·00	76,160	53·55
14·00	31,360	22·05	34·50	77,280	54·34
14·50	32,480	22·84	35·00	78,400	55·12
15·00	33,600	23·62	35·50	79,520	55·91
15·50	34,720	24·41	36·00	80,640	56·70
16·00	35,840	25·20	36·50	81,760	57·49
16·50	36,960	25·99	37·00	82,880	58·27
17·00	38,080	26·77	37·50	84,000	59·06
17·50	39,200	27·56	38·00	85,120	59·85
18·00	40,320	28·35	38·50	86,240	60·64
18·50	41,440	29·14	39·00	87,360	61·42
19·00	42,560	29·92	39·50	88,480	62·21
19·50	43,680	30·71	40·00	89,600	63·00
20·00	44,800	31·50	40·50	90,720	63·79
20·50	45,920	32·29	41·00	91,840	64·57
21·00	47,040	33·07	41·50	92,960	65·36
21·50	48,160	33·86	42·00	94,080	66·15
22·00	49,280	34·65	42·50	95,200	66·94
22·50	50,400	35·44	43·00	96,320	67·72
23·00	51,520	36·22	43·50	97,440	68·51
23·50	52,640	37·01	44·00	98,560	69·30
24·00	53,760	37·80	44·50	99,680	70·09
24·50	54,880	38·59	45·00	100,800	70·87
25·00	56,000	39·37	45·50	101,920	71·66
25·50	57,120	40·16	46·00	103,040	72·45
26·00	58,240	40·95	46·50	104,160	73·24
26·50	59,360	41·74	47·00	105,280	74·02
27·00	60,480	42·52	47·50	106,400	74·81
27·50	61,600	43·31	48·00	107,520	75·60
28·00	62,720	44·10	48·50	108,640	76·39
28·50	63,840	44·89	49·00	109,760	77·17
29·00	64,960	45·67	49·50	110,880	77·96
29·50	66,080	46·46	50·00	112,000	78·75
30·00	67,200	47·25			

WEIGHT OF STEEL BARS PER LINEAL FOOT IN POUNDS.

Round, Square, and Octagon Steel.

Size in inches.	Round.	Octagon.	Square.	Size in inches.	Round.	Octagon.	Square.
1/16	0·010	0·011	0·013	2 1/2	16·79	17·71	21·37
1/8	0·042	0·044	0·053	2 5/8	18·51	19·52	23·56
3/16	0·094	0·099	0·120	2 3/4	20·31	21·42	25·86
1/4	0·168	0·177	0·214	2 7/8	22·20	23·41	28·27
5/16	0·262	0·277	0·334	3	24·17	25·50	30·78
3/8	0·378	0·398	0·481	3 1/8	26·23	27·66	33·40
7/16	0·514	0·542	0·655	3 1/4	28·37	29·92	36·12
1/2	0·671	0·708	0·855	3 3/8	30·59	32·27	38·95
9/16	0·850	0·896	1·082	3 1/2	32·90	34·70	41·89
5/8	1·049	1·107	1·336	3 5/8	35·29	37·23	44·94
11/16	1·270	1·339	1·616	3 3/4	37·77	39·84	48·09
3/4	1·511	1·594	1·924	3 7/8	40·33	42·54	51·35
13/16	1·773	1·870	2·258	4	42·97	45·34	54·72
7/8	2·056	2·169	2·618	4 1/4	48·51	51·17	61·77
15/16	2·361	2·490	3·006	4 1/2	54·39	57·37	69·25
1	2·686	2·833	3·420	4 3/4	60·60	63·92	77·16
1 1/8	3·399	3·585	4·328	5	67·15	70·83	85·50
1 1/4	4·197	4·427	5·344	5 1/4	74·03	78·08	94·26
1 3/8	5·078	5·356	6·646	5 1/2	81·25	85·70	103·45
1 1/2	6·044	6·374	7·695	5 3/4	88·80	93·67	113·07
1 5/8	7·093	7·481	9·031	6	96·69	101·99	123·12
1 3/4	8·226	8·674	10·474	7	131·61	138·82	167·58
1 7/8	9·443	9·960	12·023	8	171·90	181·32	218·88
2	10·744	11·332	13·680	9	217·57	229·48	277·02
2 1/8	12·129	12·793	15·443	10	268·60	283·31	342·00
2 1/4	13·598	14·343	17·314	11	325·01	342·80	413·82
2 1/2	15·151	15·981	19·291	12	386·79	407·97	492·48

WEIGHT OF STEEL BARS PER LINEAL FOOT IN POUNDS.

Flats.

Inch.	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{3}{4}$	1
$\frac{1}{2}$	0·214	0·428	0·641	—	—	—	—
$\frac{5}{8}$	0·267	0·534	0·802	1·069	—	—	—
$\frac{3}{4}$	0·321	0·641	0·962	1·283	1·603	—	—
$\frac{7}{8}$	0·374	0·748	1·122	1·496	1·870	2·244	—
1	0·427	0·855	1·283	1·710	2·138	2·565	—
$1\frac{1}{8}$	0·481	0·962	1·443	1·924	2·405	2·886	3·848
$1\frac{1}{4}$	0·534	1·069	1·603	2·138	2·672	3·206	4·278
$1\frac{3}{8}$	0·588	1·176	1·763	2·351	2·939	3·527	4·703
$1\frac{1}{2}$	0·641	1·283	1·924	2·565	3·206	3·848	5·130
$1\frac{5}{8}$	0·695	1·389	2·084	2·779	3·473	4·168	5·558
$1\frac{3}{4}$	0·748	1·496	2·244	2·993	3·741	4·489	5·985
$1\frac{7}{8}$	0·802	1·603	2·405	3·206	4·008	4·809	6·413
2	0·855	1·710	2·565	3·420	4·275	5·130	6·840
$2\frac{1}{8}$	0·908	1·817	2·725	3·634	4·542	5·451	7·268
$2\frac{1}{4}$	0·962	1·924	2·886	3·848	4·809	5·771	7·695
$2\frac{3}{8}$	1·015	2·031	3·046	4·061	5·077	6·092	8·123
$2\frac{1}{2}$	1·069	2·138	3·206	4·275	5·344	6·413	8·550
$2\frac{5}{8}$	1·122	2·244	3·367	4·489	5·611	6·733	8·978
$2\frac{3}{4}$	1·176	2·351	3·527	4·703	5·878	7·054	9·405
3	1·283	2·565	3·848	5·130	6·413	7·695	10·260
$3\frac{1}{4}$	1·389	2·779	4·168	5·558	6·947	8·336	11·115
$3\frac{1}{2}$	1·496	2·993	4·489	5·985	7·481	8·978	11·970
$3\frac{3}{4}$	1·603	3·206	4·809	6·413	8·016	9·619	12·825
4	1·710	3·420	5·130	6·840	8·550	10 260	13·680
$4\frac{1}{4}$	1·817	3·634	5·451	7·268	9·084	10·901	14·535
$4\frac{1}{2}$	1·924	3·848	5·771	7·695	9·619	11·542	15·390
$4\frac{3}{4}$	2·031	4·061	6·092	8·123	10·153	12·184	16·245
5	2·138	4·275	6·413	8·550	10·688	12·825	17·100
$5\frac{1}{4}$	2·244	4·489	6·733	8·978	11·222	13·466	17·955
$5\frac{1}{2}$	2·351	4·703	7·054	9·405	11·756	14·108	18·810
$5\frac{3}{4}$	2·458	4·916	7·374	9·833	12·291	14·749	19·665
6	2·565	5·130	7·695	10·260	12·825	15·390	20·520

TABLE OF RELIABLE MELTING POINTS.

(DR. J. A. HARKER.)

	Centigrade.	Fahrenheit.
Melting point of zinc	419	786
„ „ antimony	632	1169
„ „ aluminium	657	1214
„ „ common salt	800	1472
„ „ silver (in air)	955	1751
„ „ „ (in reducing atmosphere	962	1763
„ „ gold	1064	1947
„ „ copper (in air)	1062	1943
„ „ potassium sulphate	1070	1958
„ „ copper in reducing atmosphere	1084	1983
„ „ nickel	1427	2600
„ „ pure iron	1503	2737
„ „ platinum	1710	3110

INDEX

THE END

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